Peeking into the Web PKI

Uncovering the Trust That Sustains Web Server Authentication

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Oregon State University
2024.05.02

Web Server Authentication

Billions of users

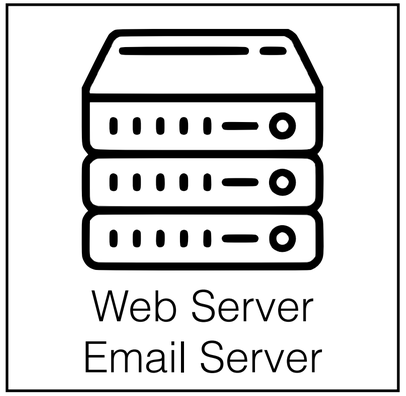
HTTPS/TLS

Millions of servers

First step in securing the Web:
messaging, websites, email, etc.

Background

paypal.com



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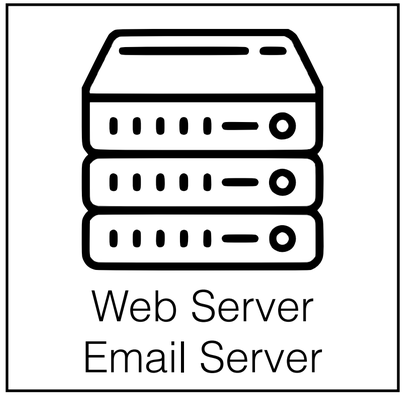

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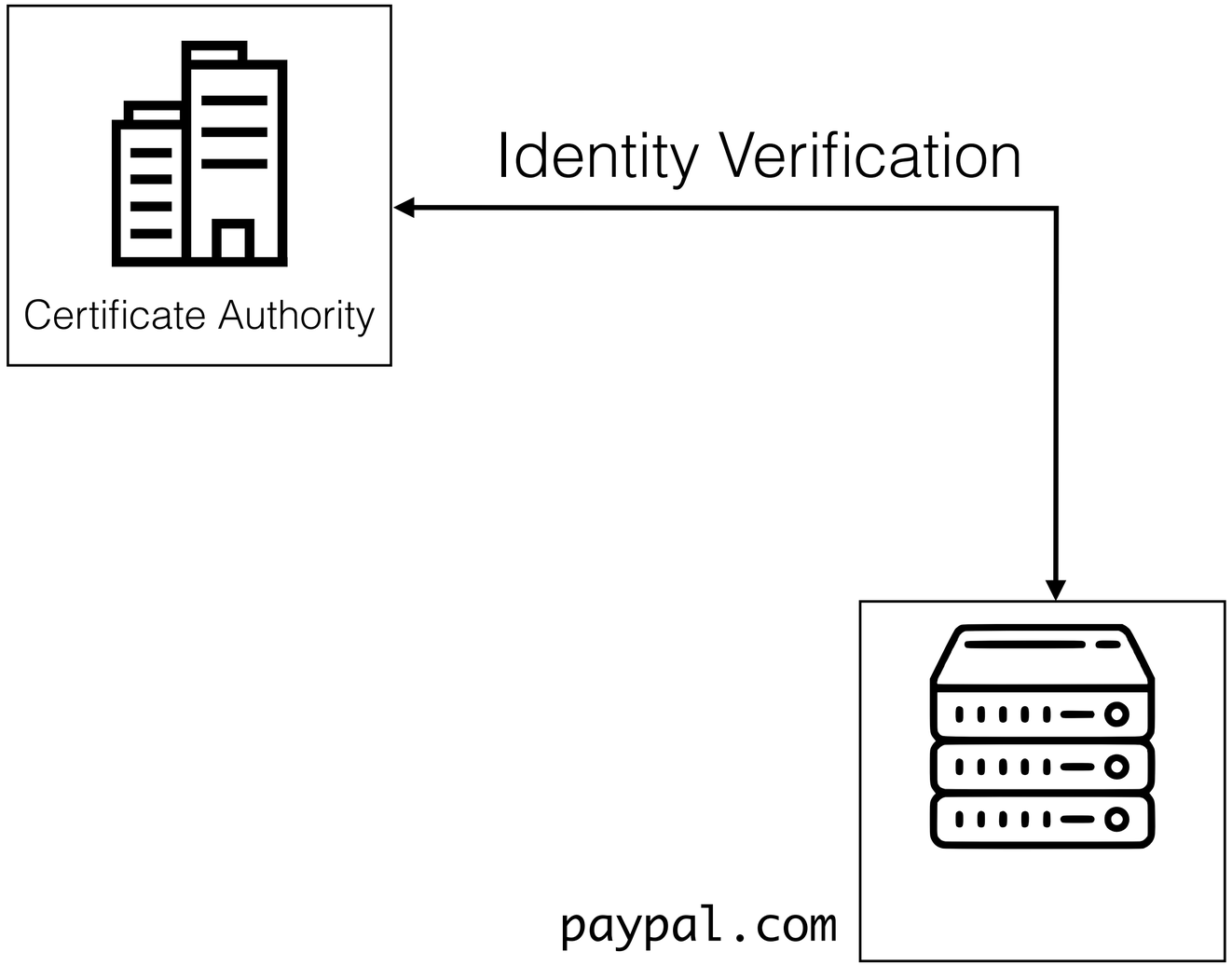
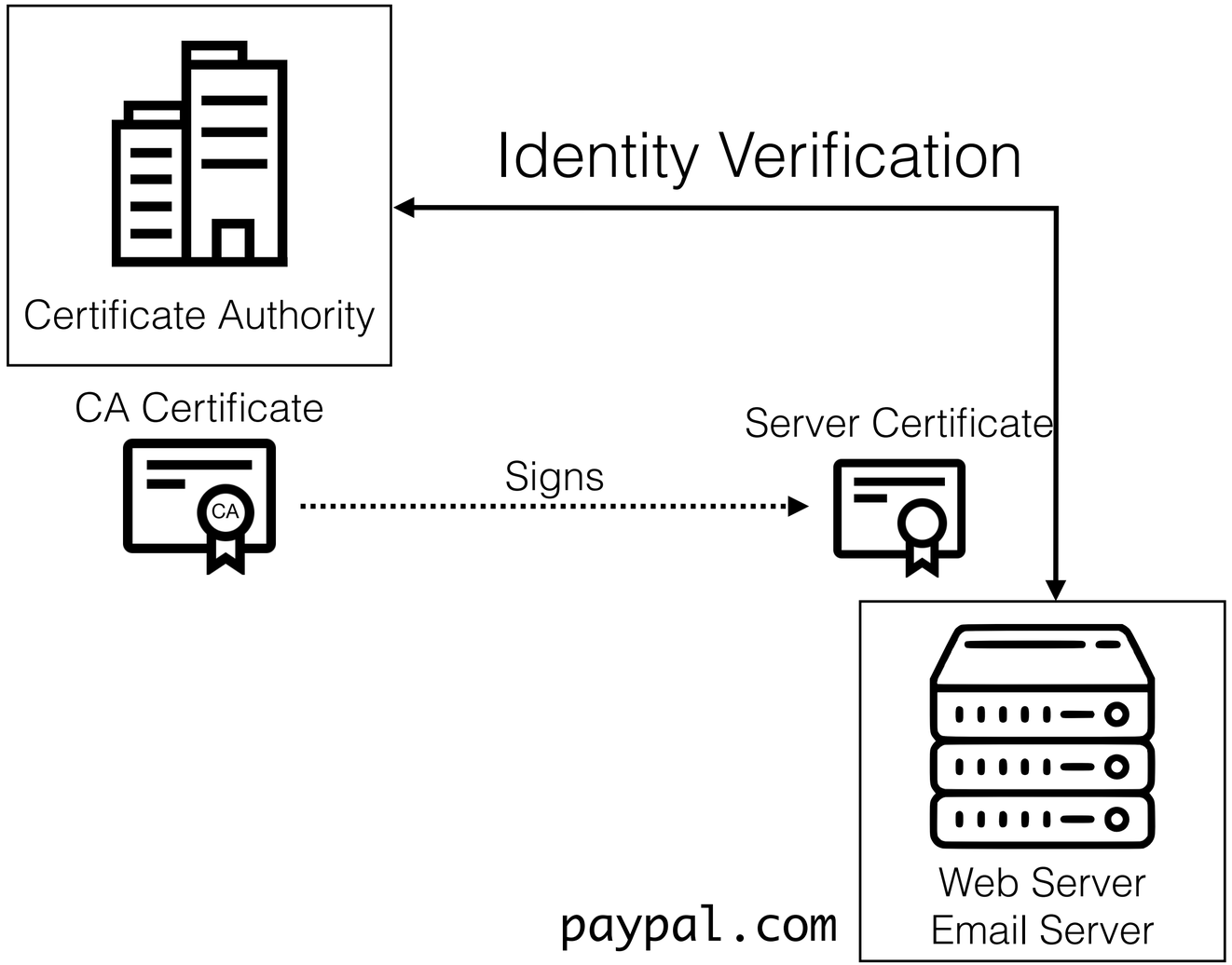

Certificate Authority
Identity Verification
paypal.com

www

Background


Certificate Authority
Identity Verification
CA Certificate
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Signs
Server Certificate
paypal.com
Web Server
Email Server

Web Browser
Email Client

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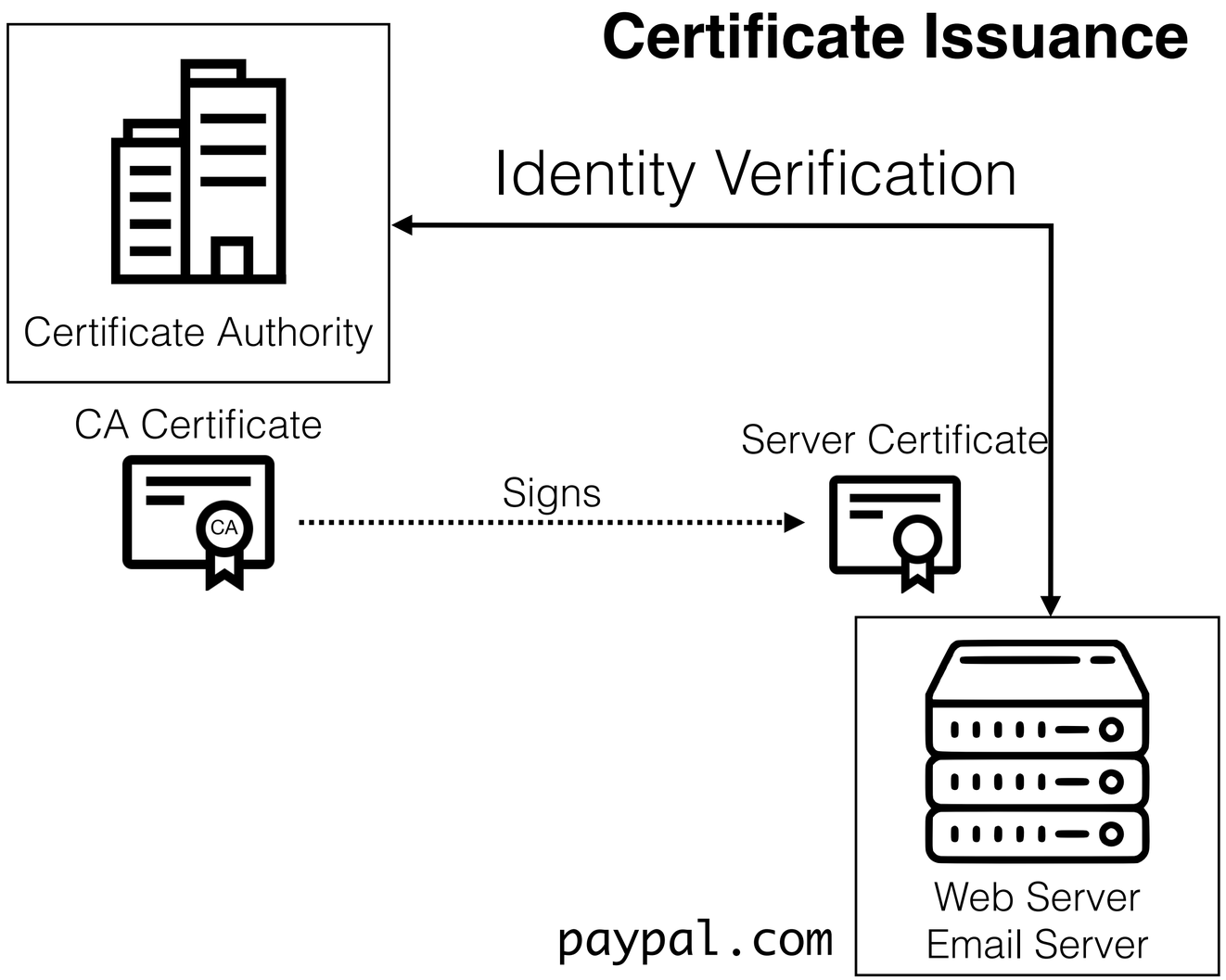
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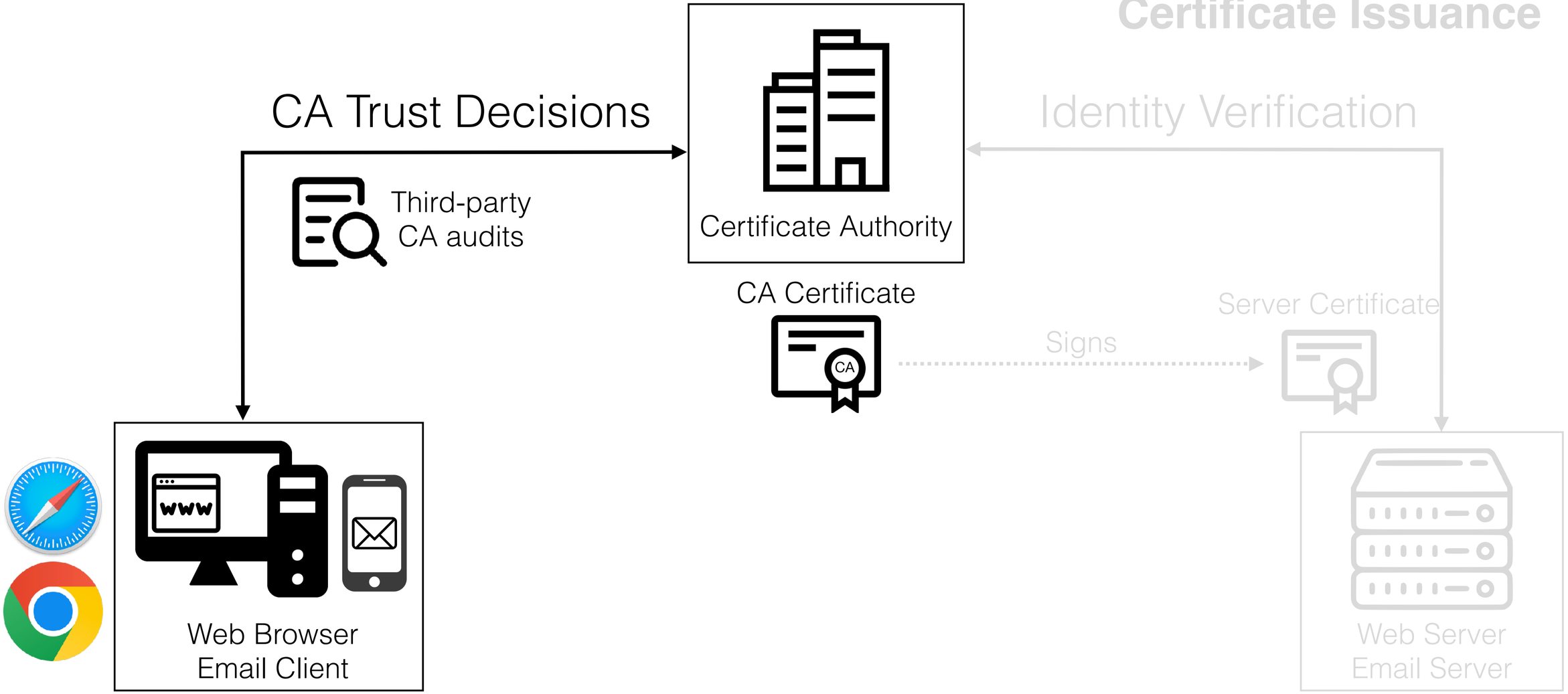
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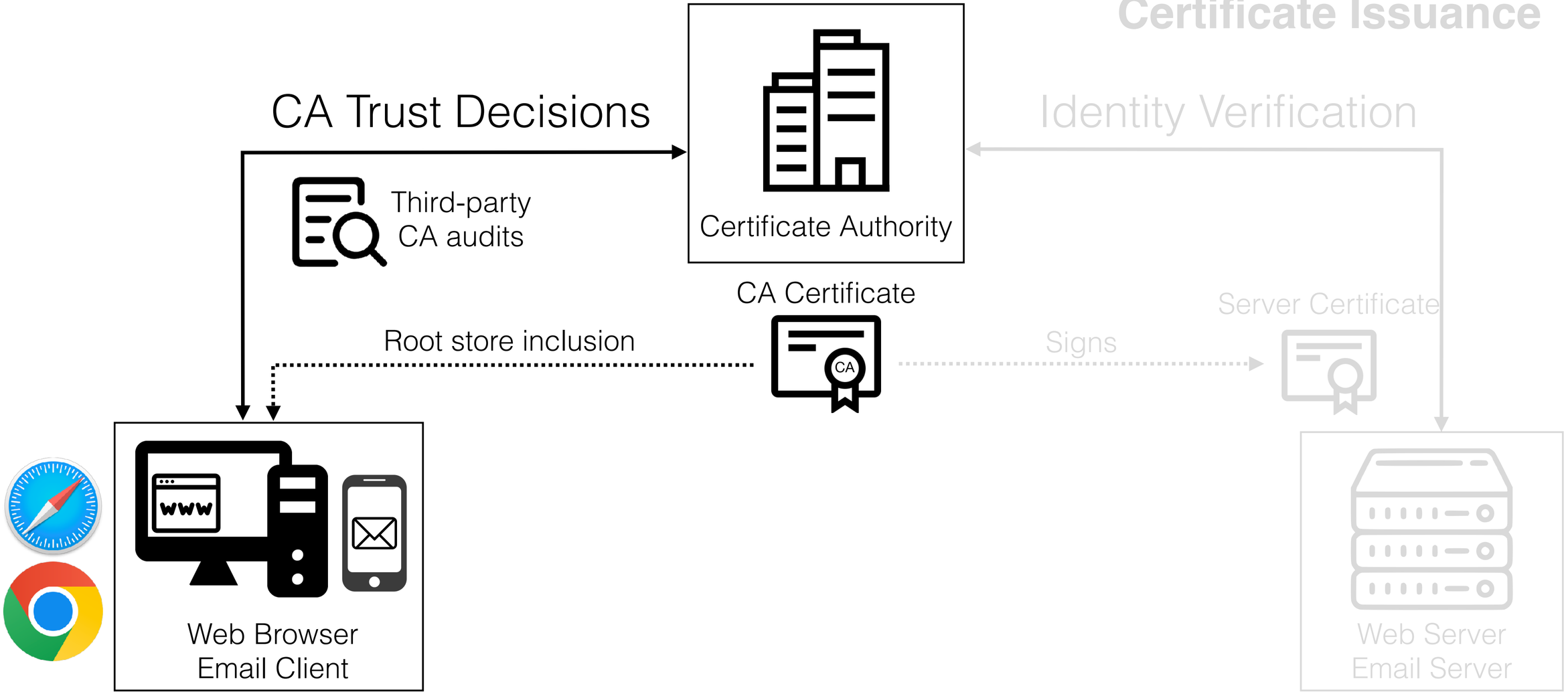
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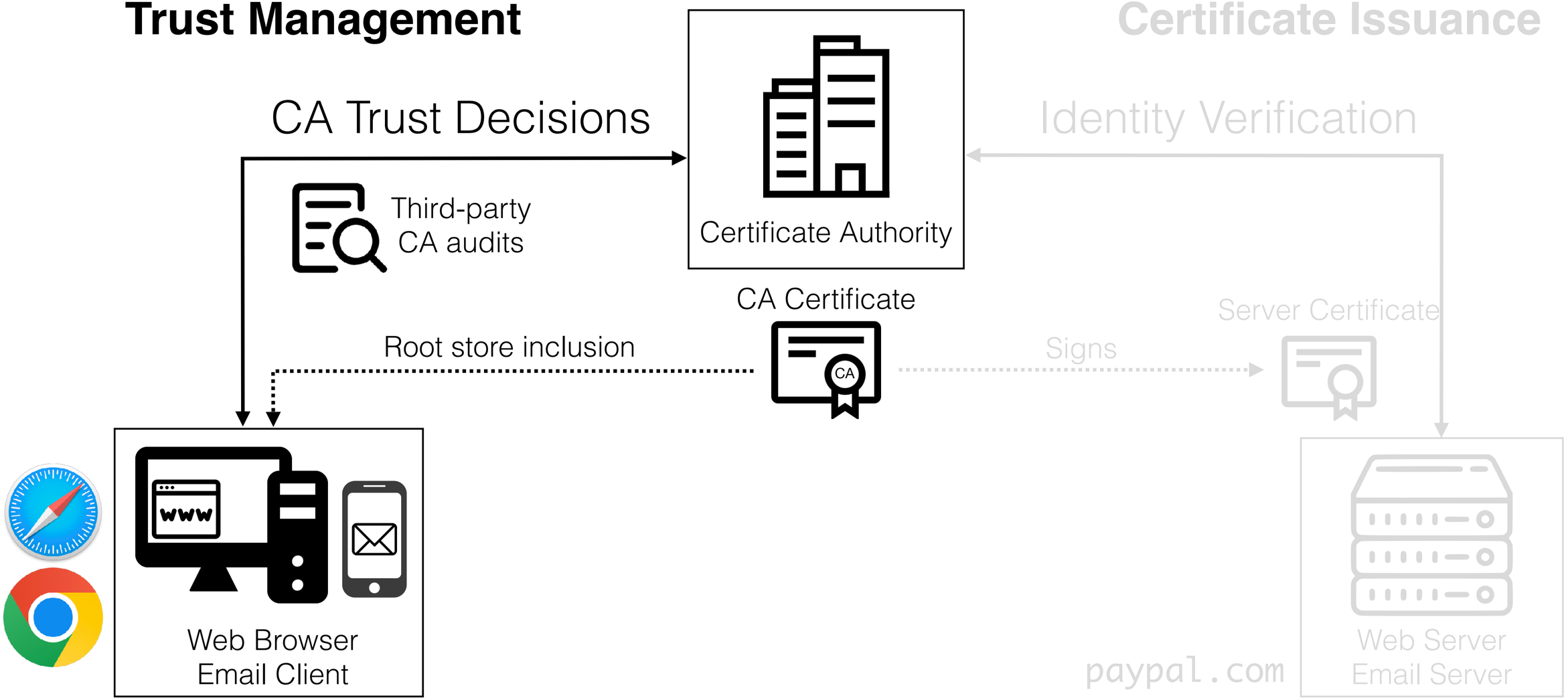
Background

Trust Management



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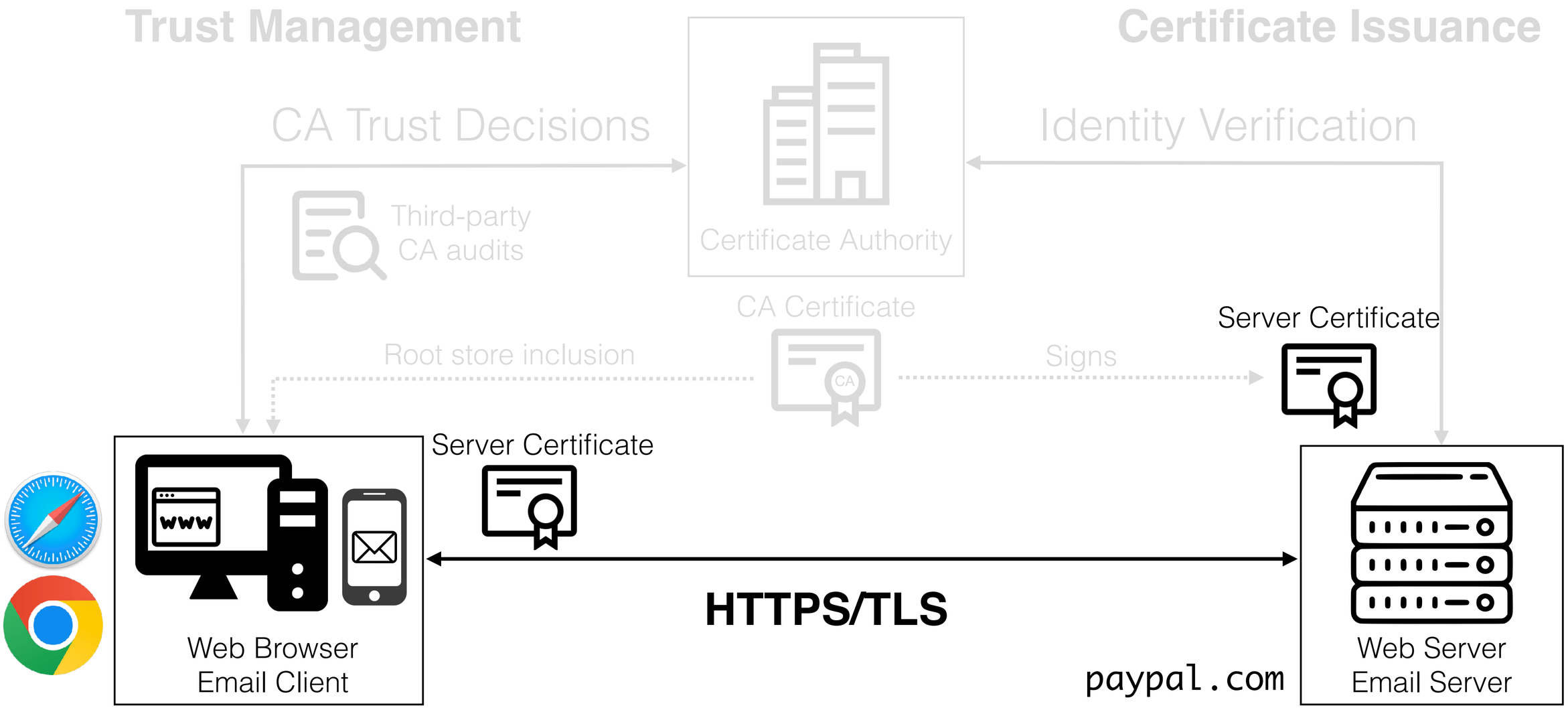
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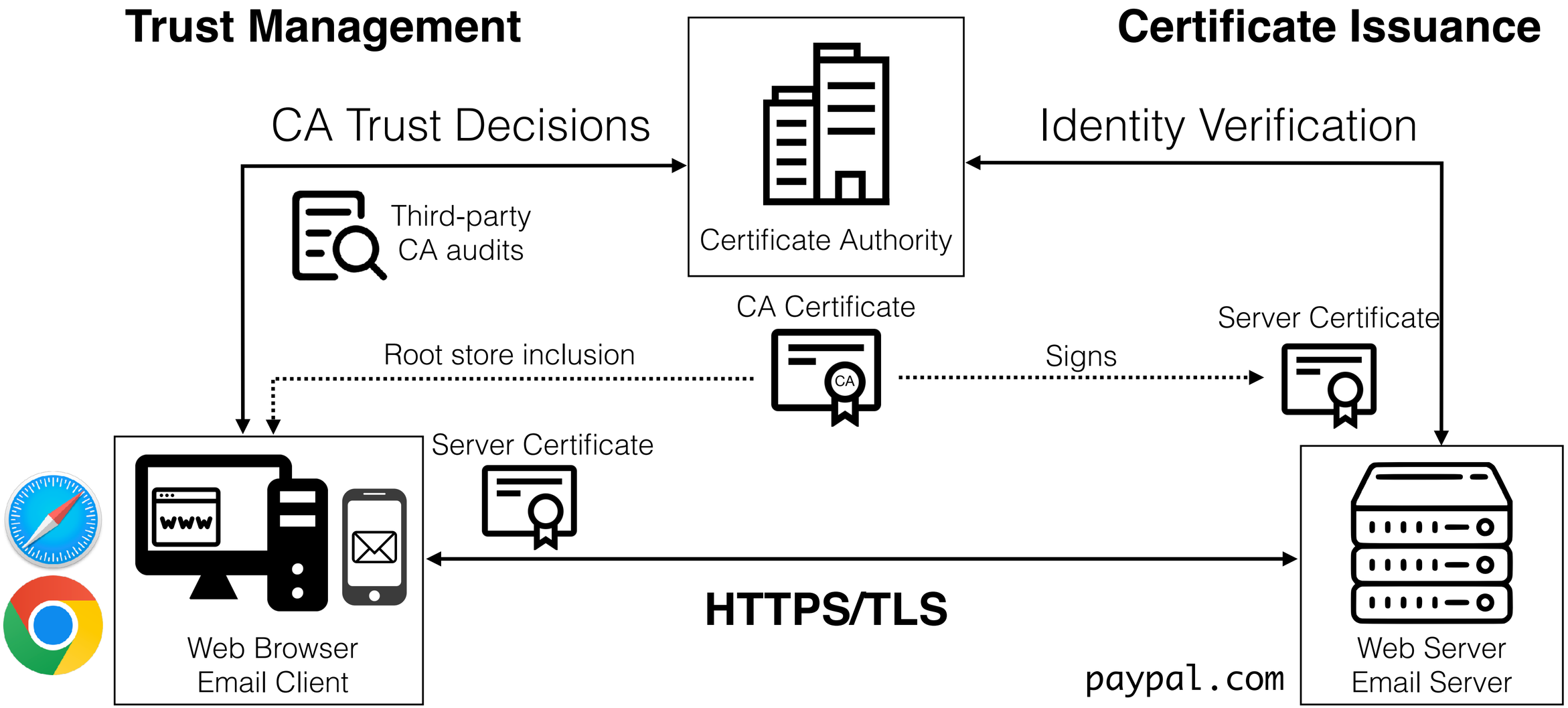
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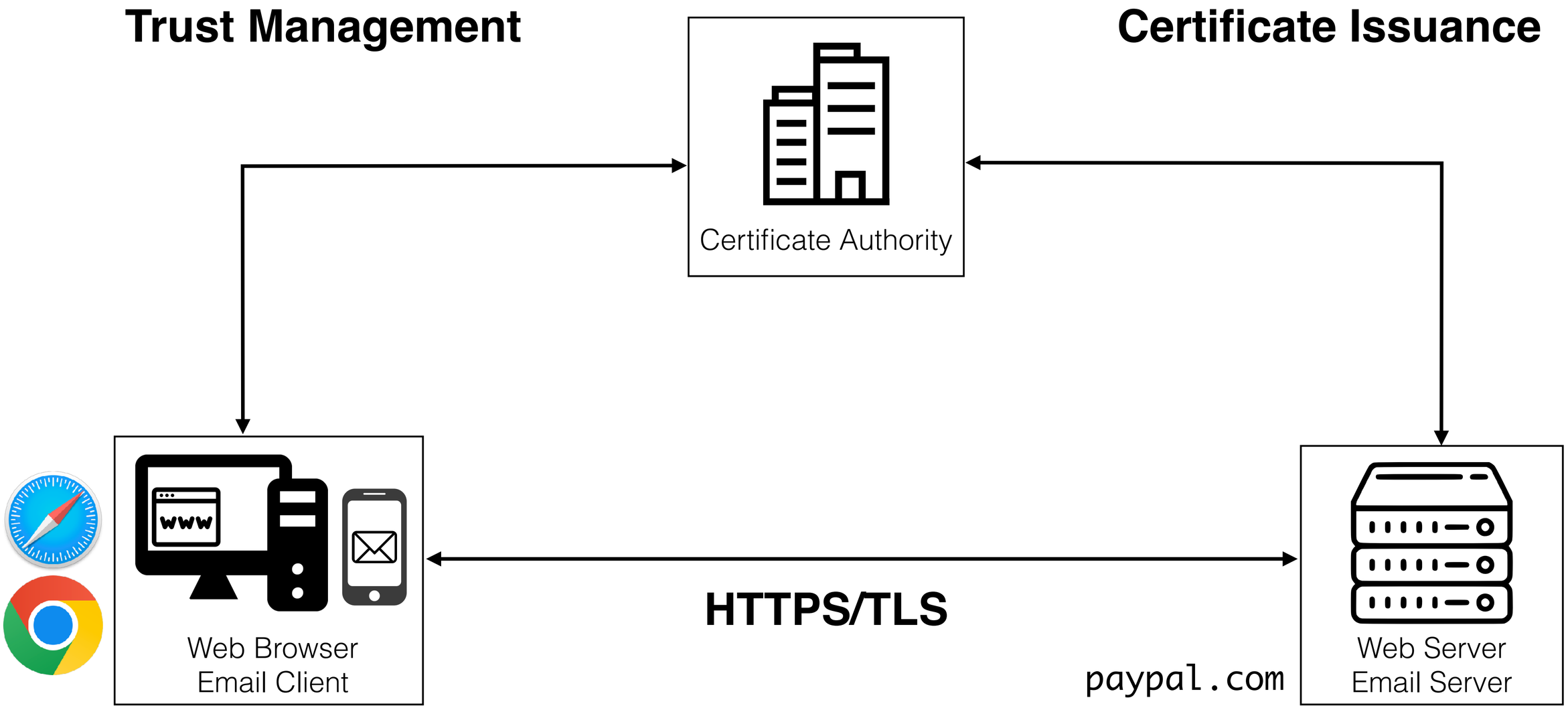
Threat Model



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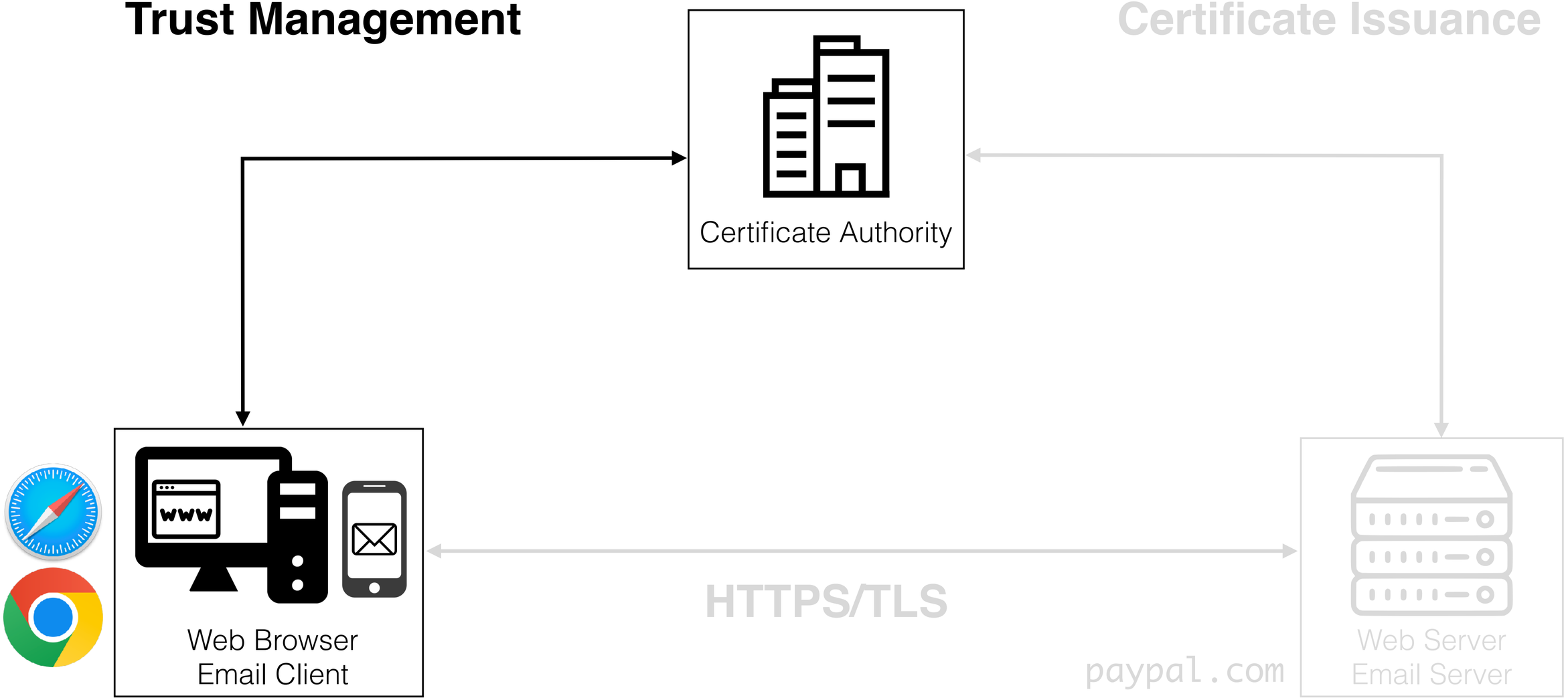

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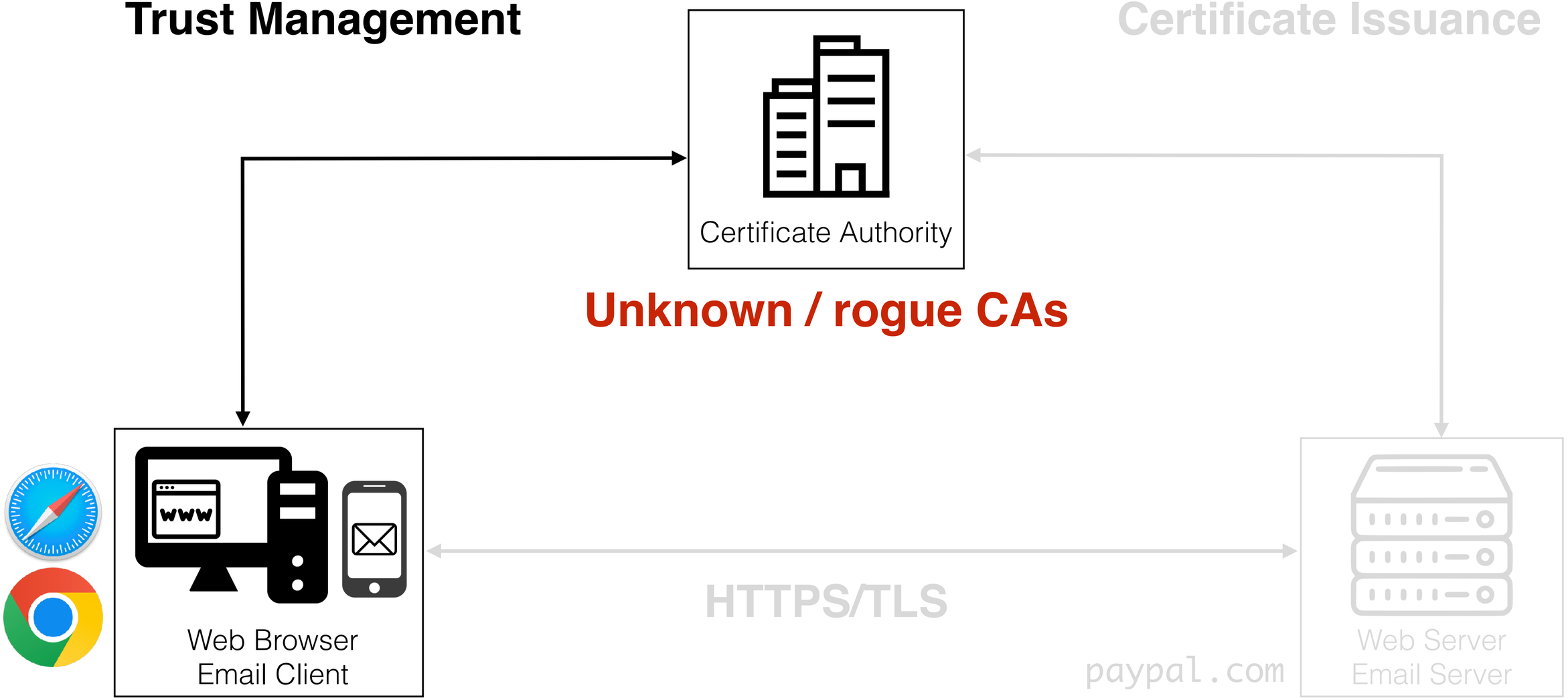

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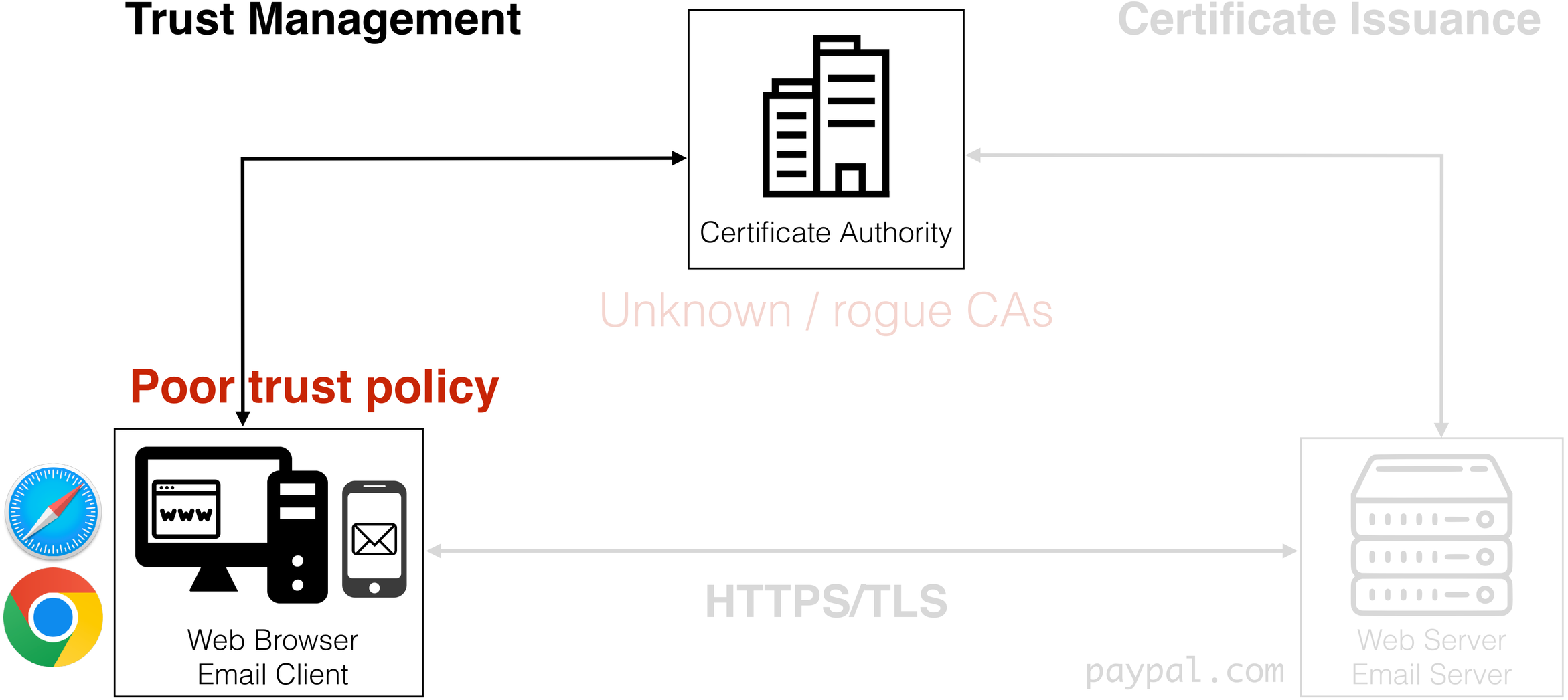

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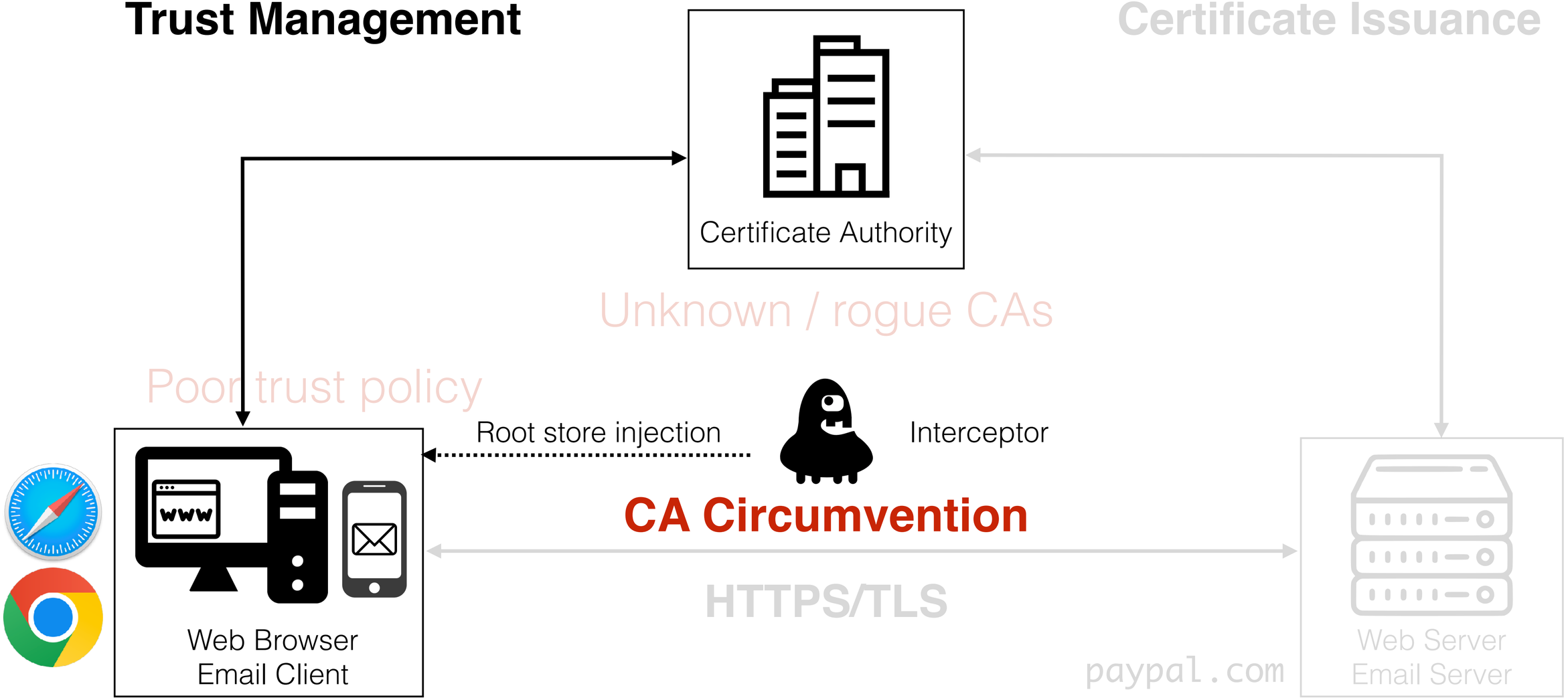

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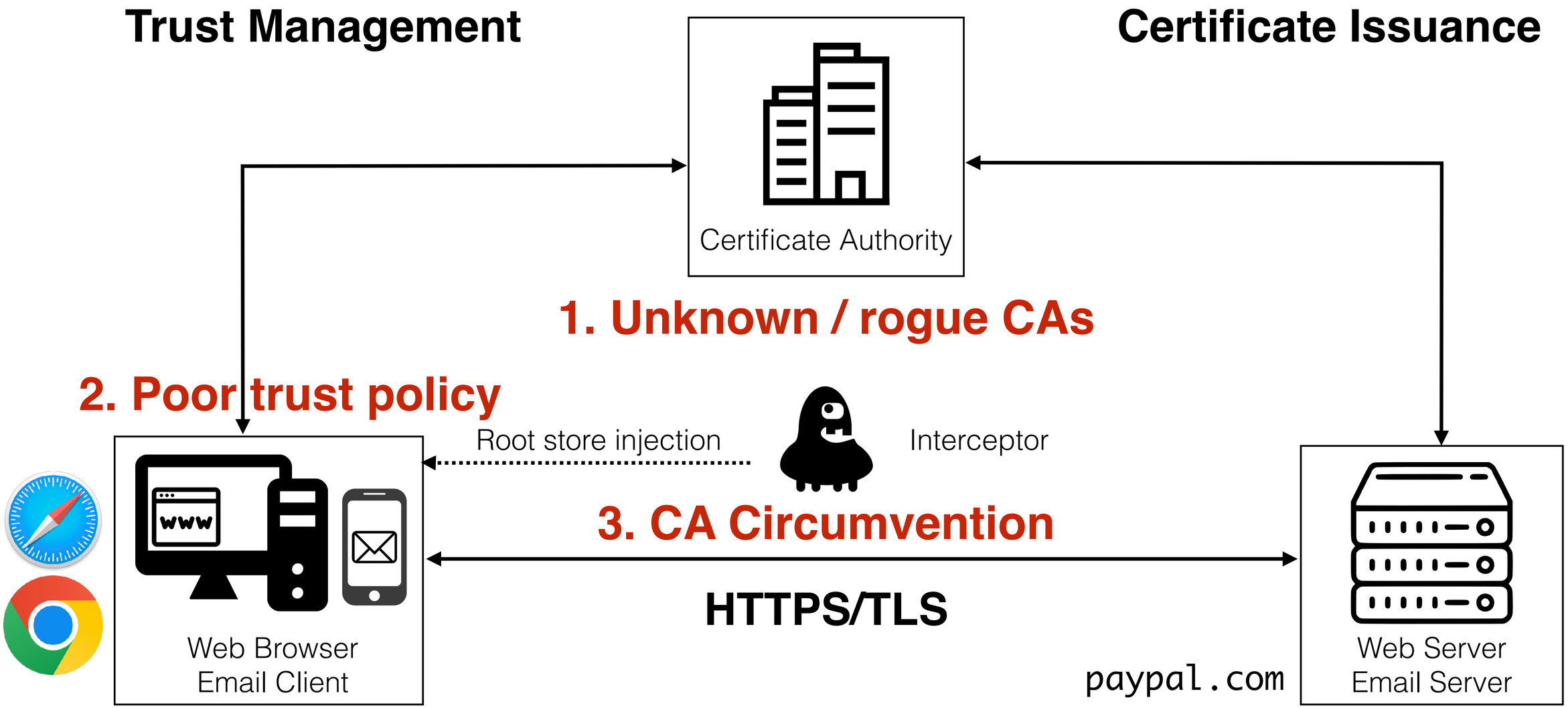
Trust Management
Certificate Issuance
Certificate Authority
1. Unknown / rogue CAs
2. Poor trust policy
Root store injection
Interceptor
3. CA Circumvention
HTTPS/TLS
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Email Client
paypal.com
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Symantec Distrust

- From 2009-2017 Symantec was responsible for over a dozen issues[1] that prompted removal from browser root stores
- Difficult to determine which CA certificates Symantec operated!

[1] https://wiki.mozilla.org/CA:Symantec_Issues

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orgName              = The USERTRUST Network
localityName         = Salt Lake City
stateOrProvinceName  = UT
countryName          = US
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CA cert #1

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CA cert #2

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Symantec CA cert #2

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Observations

1. Gap between what is trusted (CAs) and how it is enforced (CA certificates).

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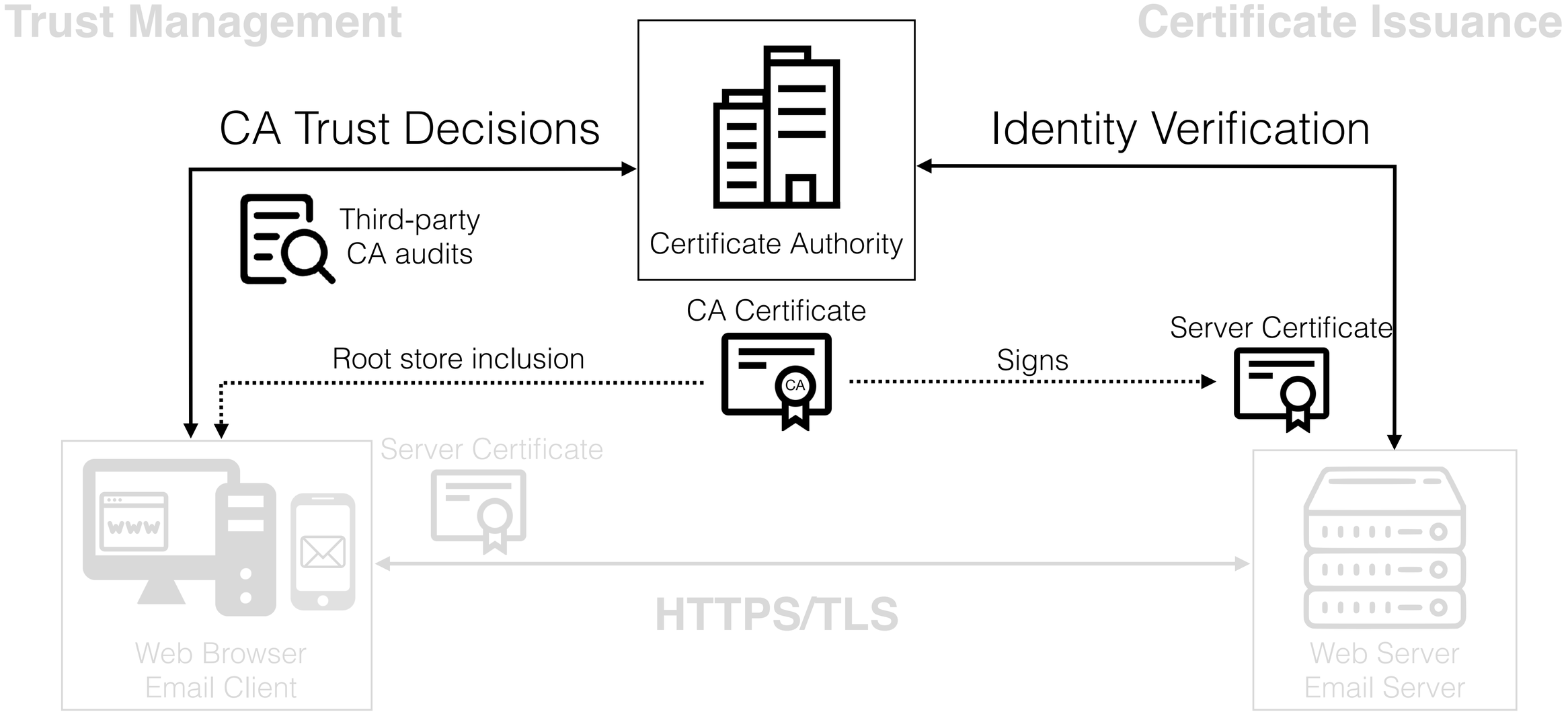
2. There are no guarantees that the identity in a CA certificate reflects the operator of the CA certificate.

Approach

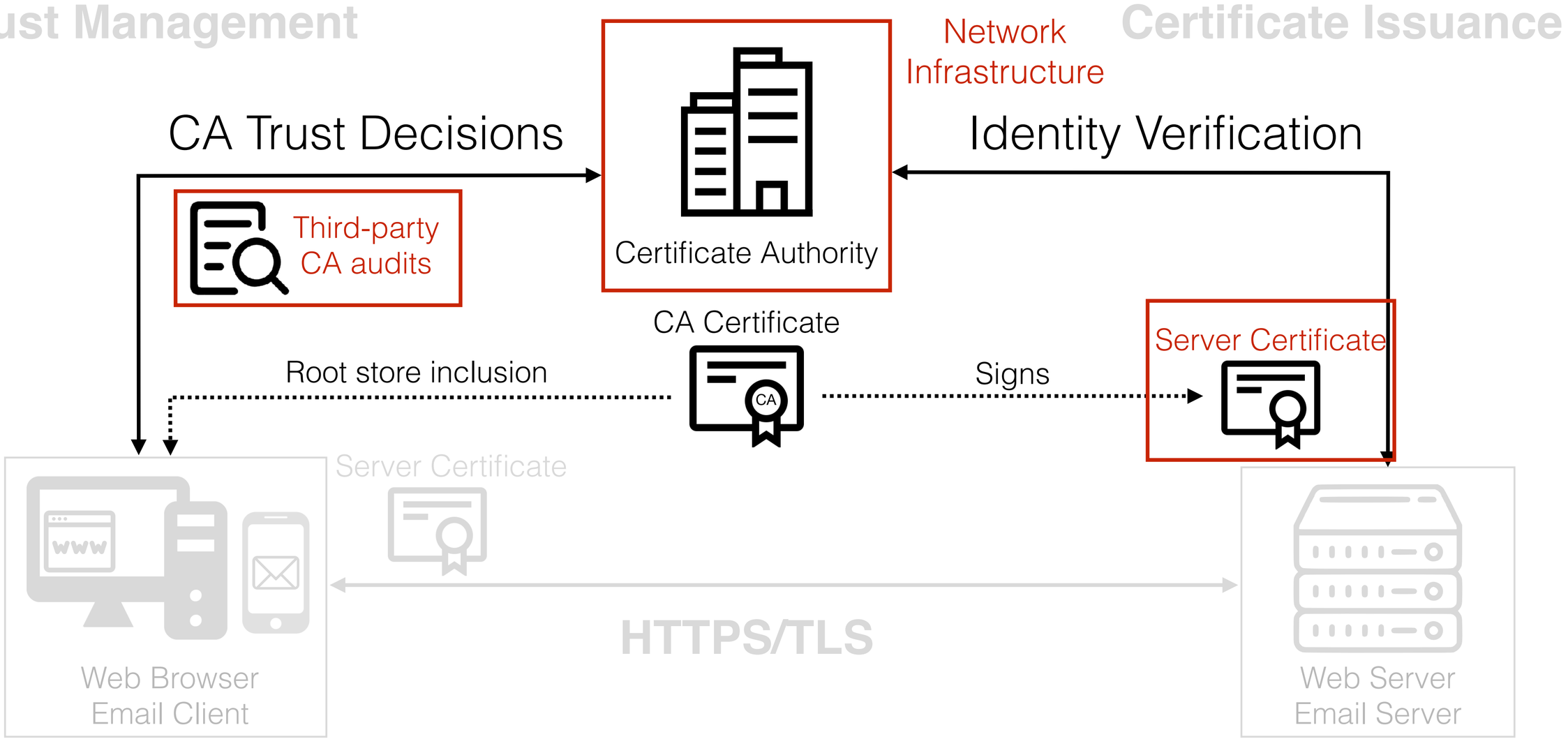
How can we build a system to determine the *operator* of a CA certificate / issuer?

1. Measure CA operational features

Perspectives on CA Operations



Perspectives on CA Operations



Approach

1. Measure CA operational features

Audits

+

Network Infra.

+

Certificates

Approach

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Audits

Reports from in-person visits to CA facilities

Incomplete; only verify minimum requirements or what is self-reported

Network Infra.

Certificates

Approach

1. Measure CA operational features

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Audits	Network Infra.	Certificates
Reports from in-person visits to CA facilities	Direct measurement of CA functional endpoint	
Incomplete; only verify minimum requirements or what is self-reported	Often obscured by network indirection (e.g., CDNs)	

Approach

1. Measure CA operational features

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Audits	Network Infra.	Certificates
Reports from in-person visits to CA facilities	Direct measurement of CA functional endpoint	Goal: distinctive measurement of a CA's certificate issuance process
Incomplete; only verify minimum requirements or what is self-reported	Often obscured by network indirection (e.g., CDNs)	

Certificate Fingerprints

Certificate Fingerprints

```
Certificate root
   TBS certificate
      Validity
         datetime:start
         datetime:end
      Subject
         Field
            oid:commonName
            string:name
         Field
            oid:organizationName
            string:name
      Extensions
         Extension
            oid:keyUsage
         Extension
            oid:basicConstraints
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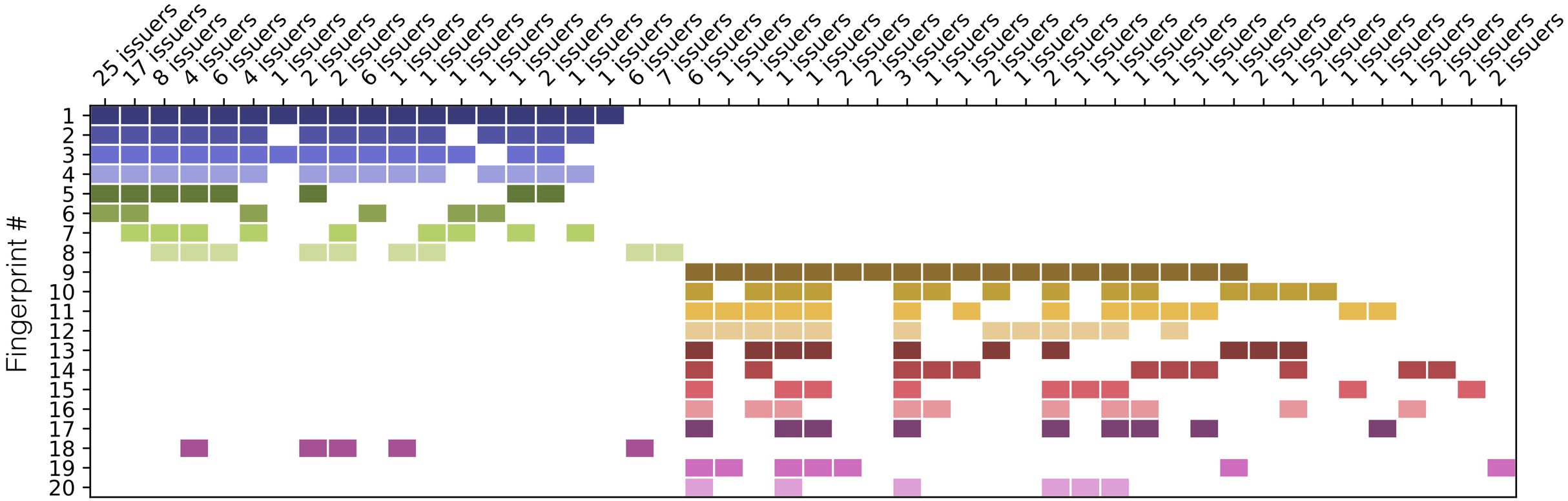

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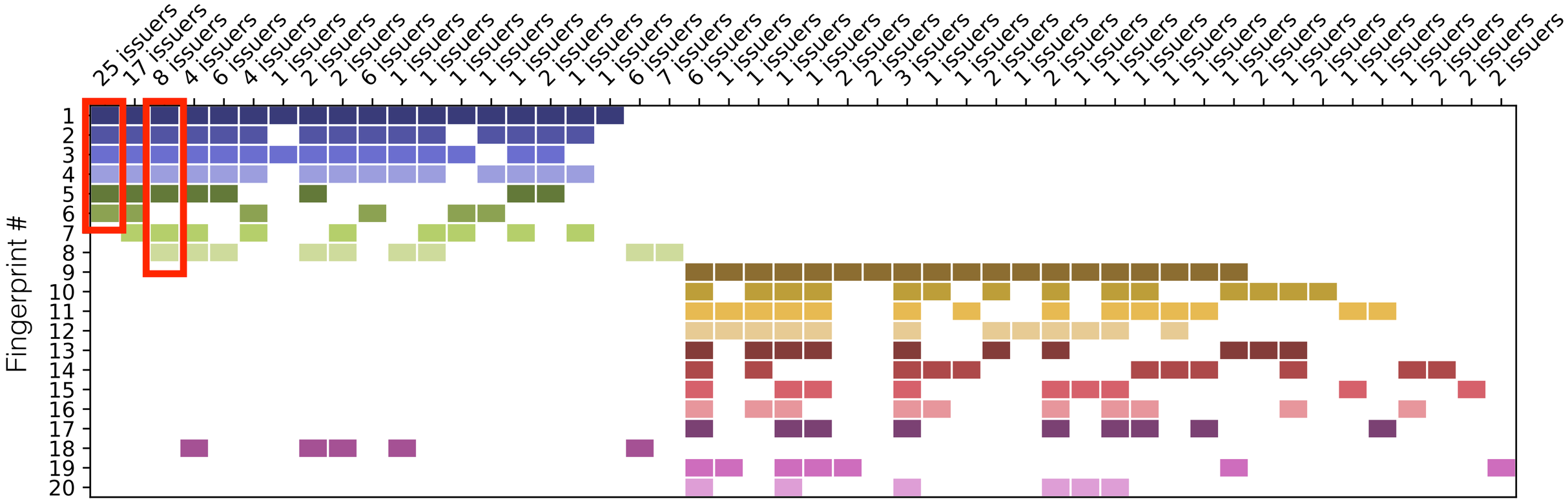

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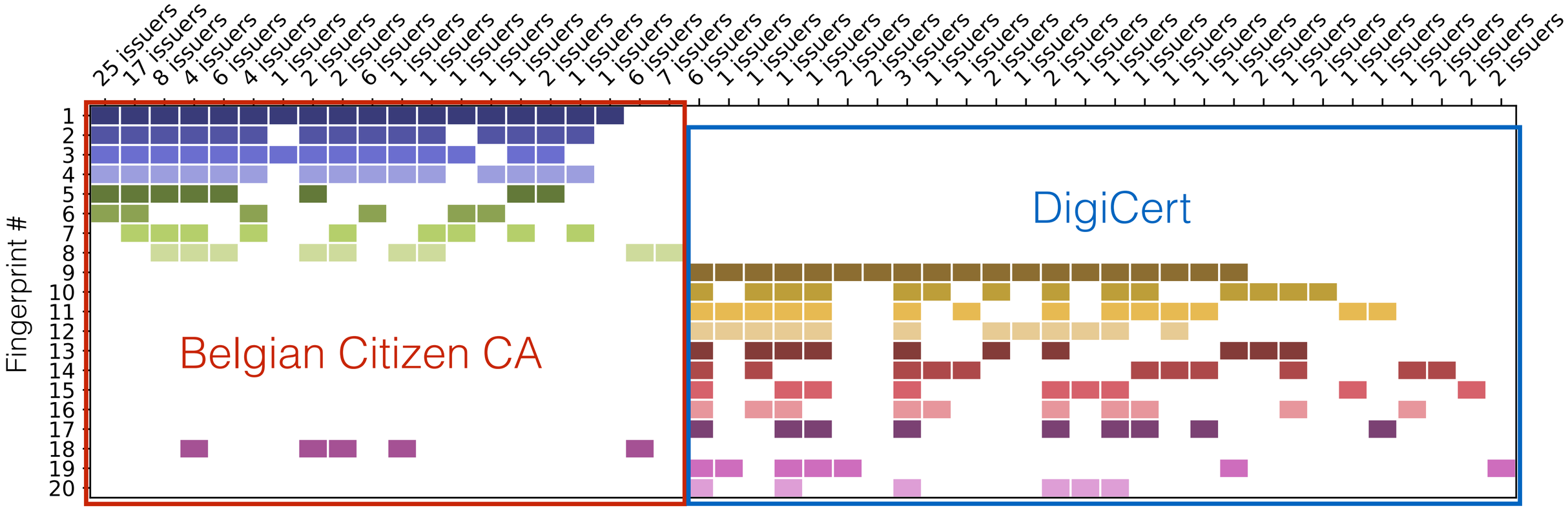

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1. Measure CA operational features

Audits

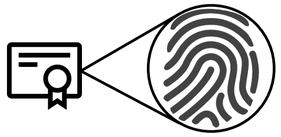
Reports from in-person visits to CA facilities

Incomplete; only verify minimum requirements or what is self-reported

Network Infra.

Direct measurement of CA functional endpoint

Often obscured by network indirection (e.g., CDNs)



Cert. Fingerprints

Isolates core CA operation - certificate issuance software

High precision, retroactive detection

Approach

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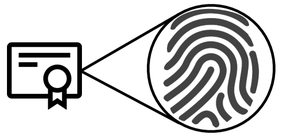

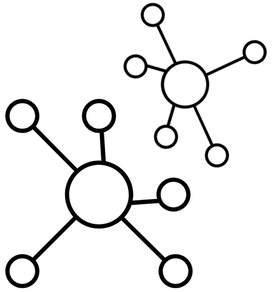

CA operator clusters

Audits	Network Infra.	Cert. Fingerprints
Reports from in-person visits to CA facilities	Direct measurement of CA functional endpoint	Isolates core CA operation - certificate issuance software
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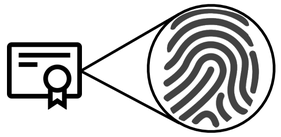

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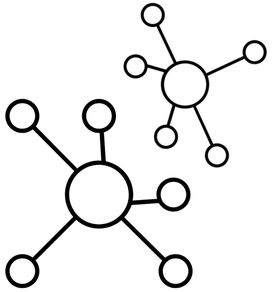

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Unlabeled!

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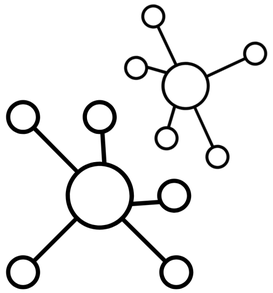
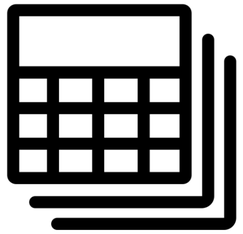


CA operator clusters

+

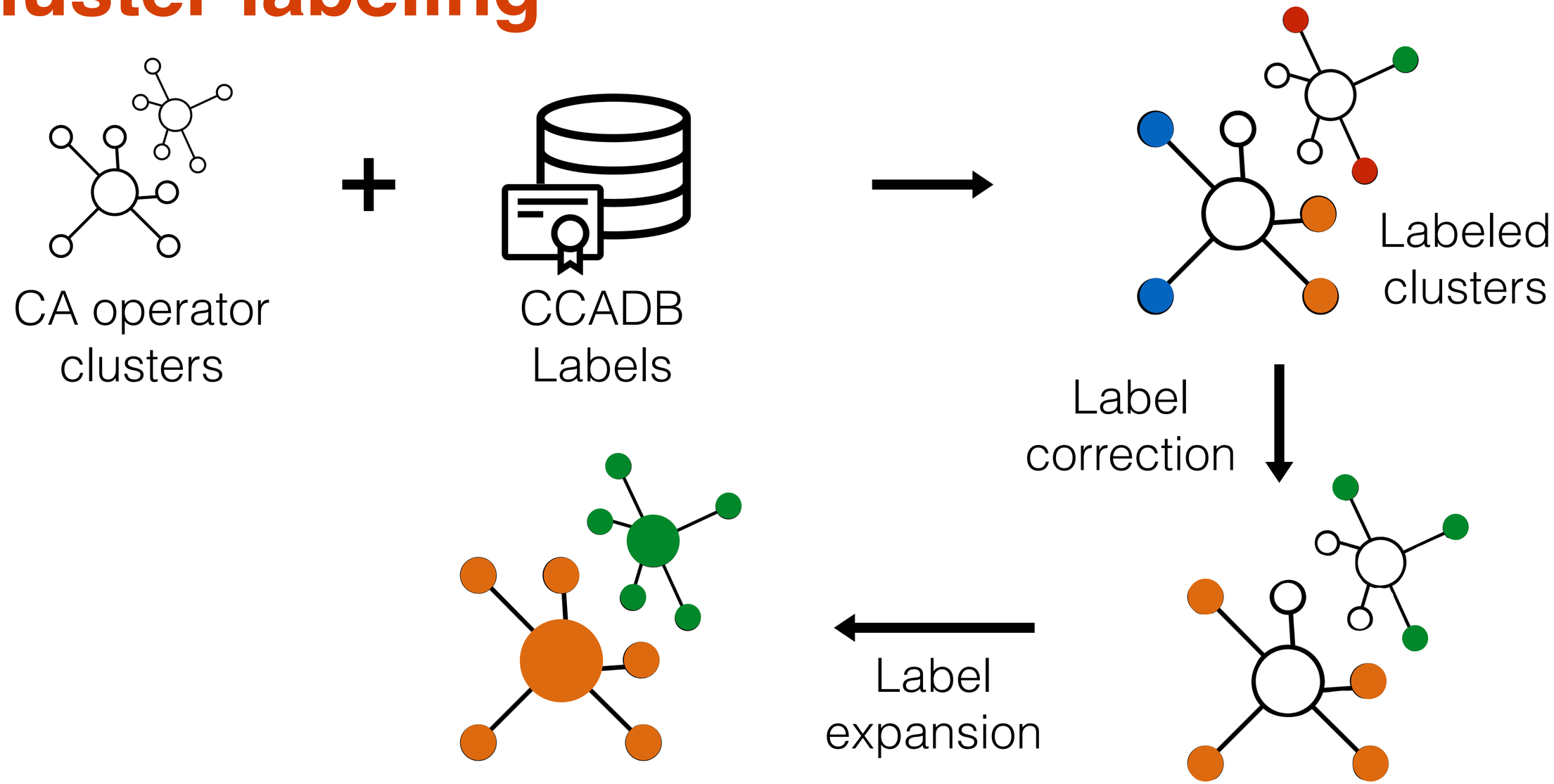
CCADB Labels

Label correction and expansion →

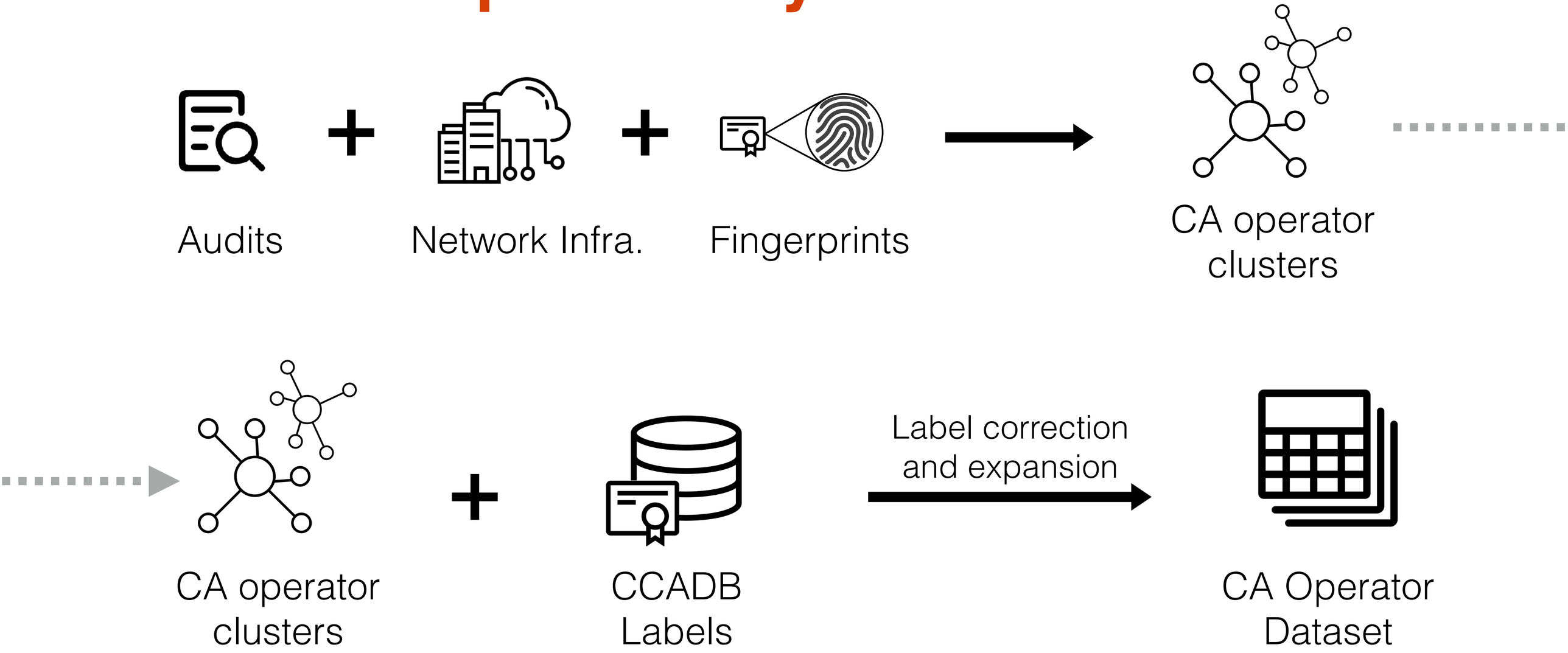


CA Operator Dataset

Cluster labeling



Fides: CA Operator System



Results

Finding	Outcome
Found trusted rogue CA (MULTICERT)[1] harbored by Camerfirma CA	Camerfirma removed from Mozilla root store, distrusted by Google products + Apple

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CA operational **transparency** means:

1) More accurate data for issuer attribution

2) More informed root store decision making

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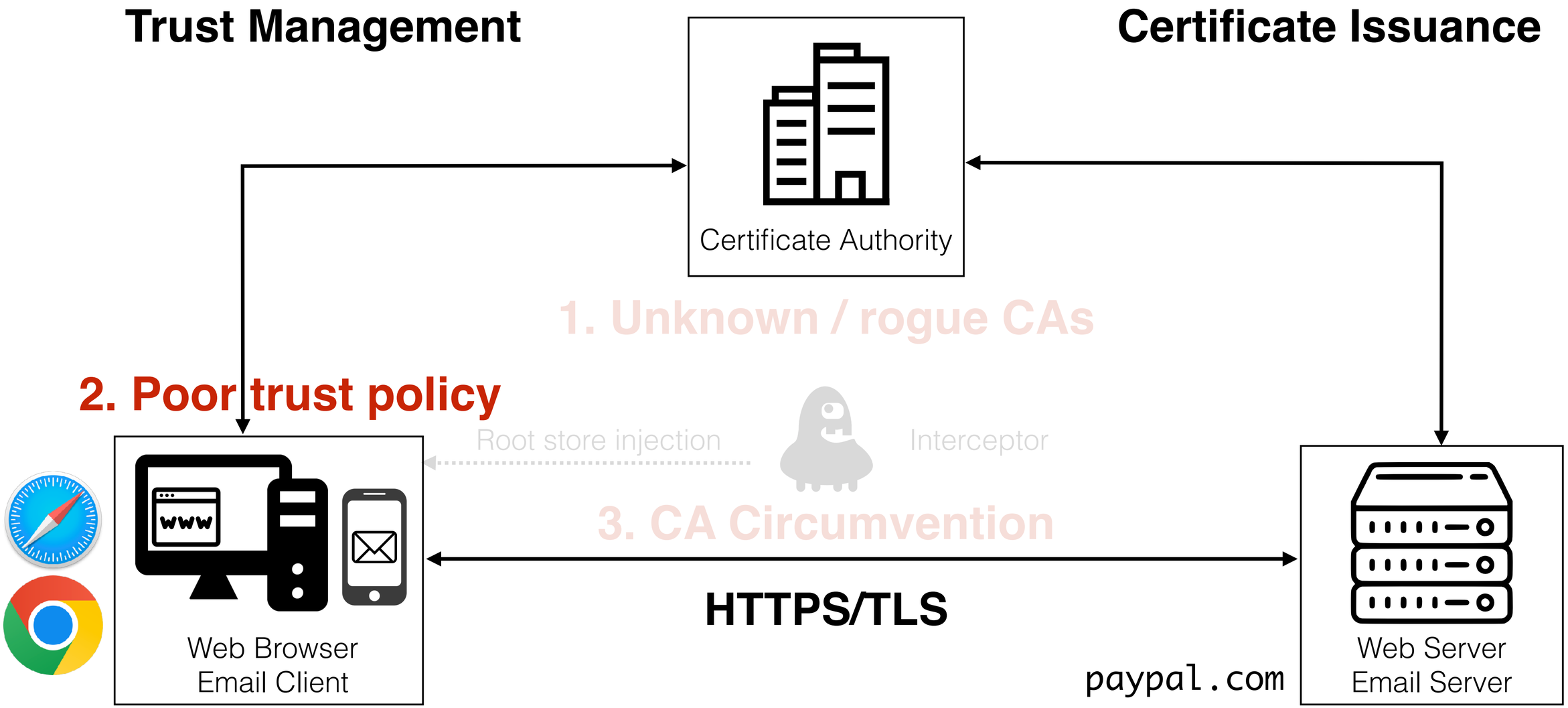
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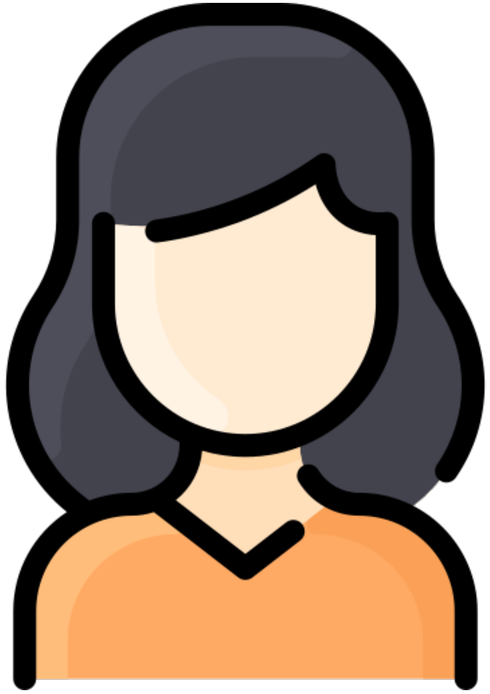
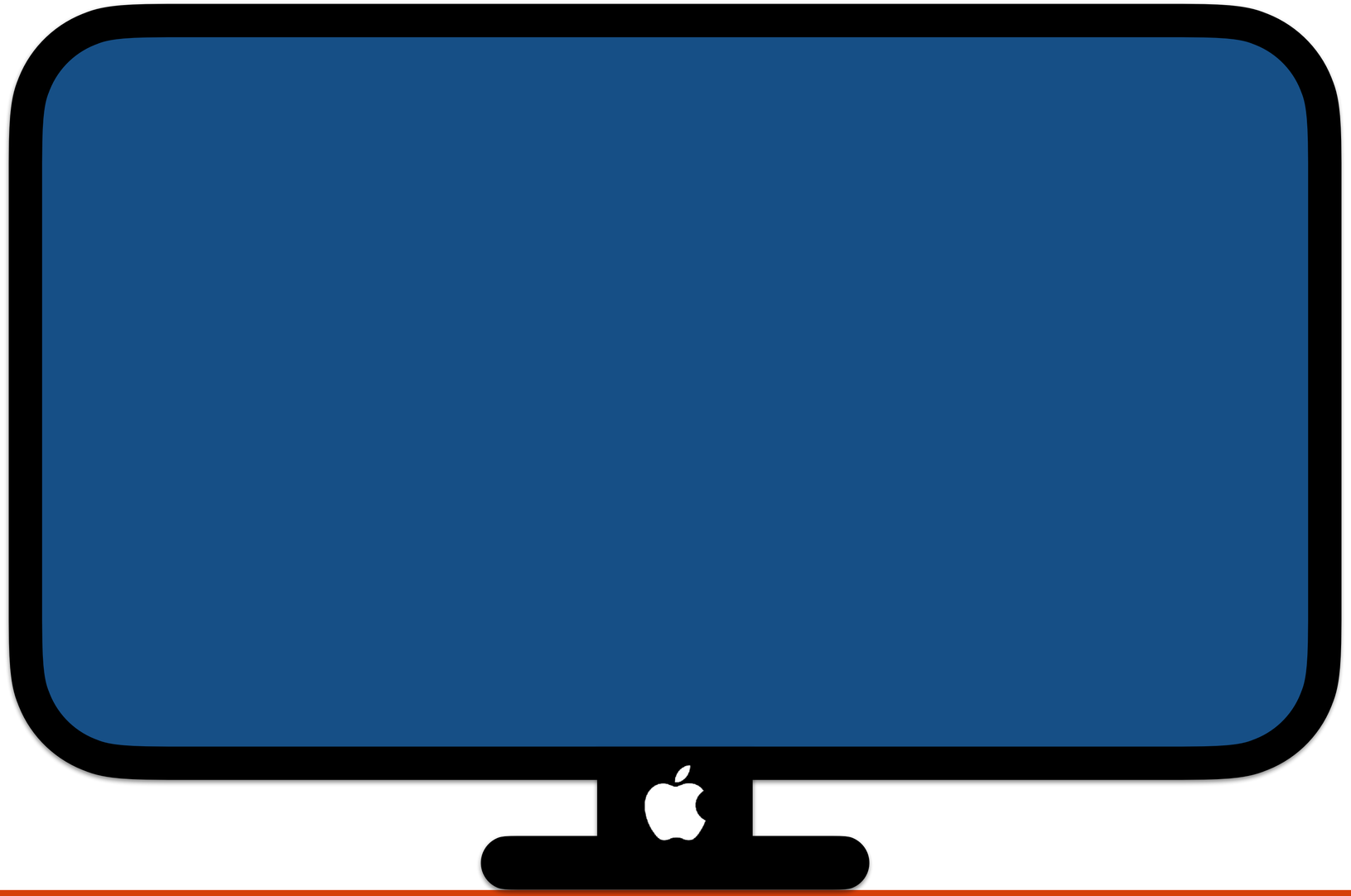
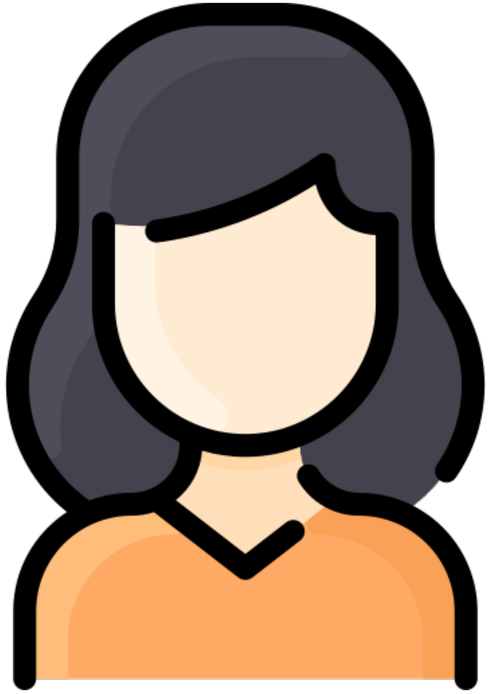
TLS user agents





TLS user agents



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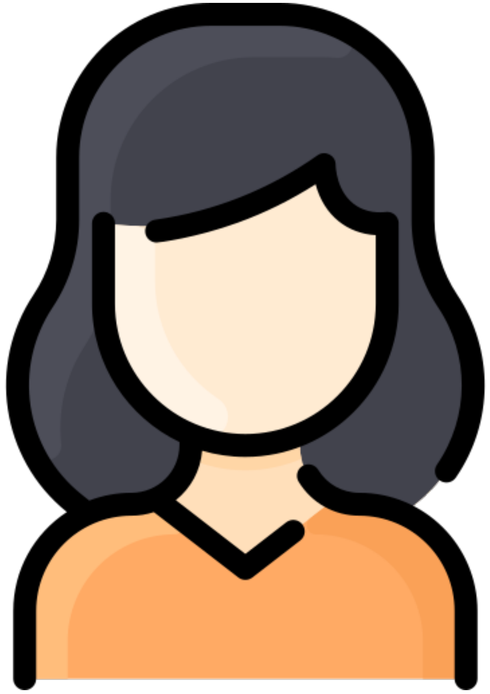

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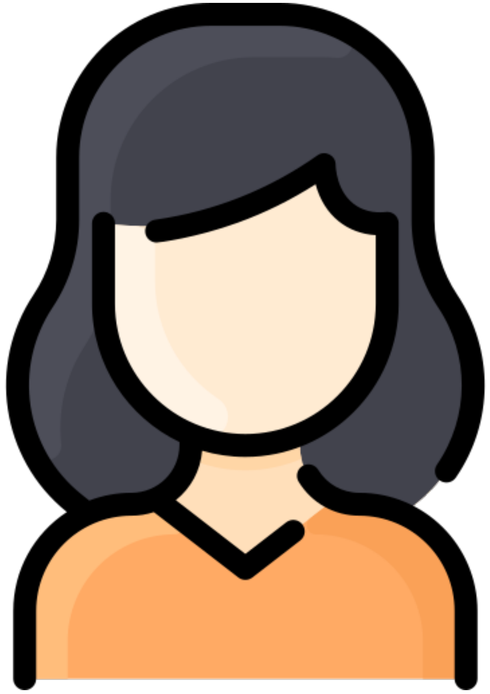

TLS user agents

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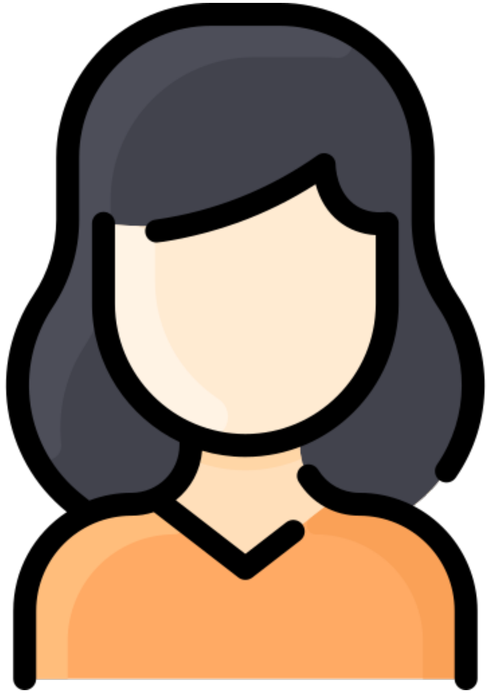

Research Questions

1. Which root store providers do TLS user agents rely on?
2. How do root store providers determine which CAs to trust?
3. Characterization of root store programs
4. How faithfully do providers copy root program trust?

TLS user agents

Challenge: Lots of TLS user agents

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Approach:

1) Study popular user agents, look at the top 200 for global CDN

2) Best-effort collection of popular libraries / clients / OSes

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Limitations: misses the long tail of TLS authentication trust

Data collection

User Agents

Web Browsers

- Chrome
- Chrome Mobile
- Opera
- Firefox
- Safari
- Mobile Safari
- Edge
- IE
- Chromium

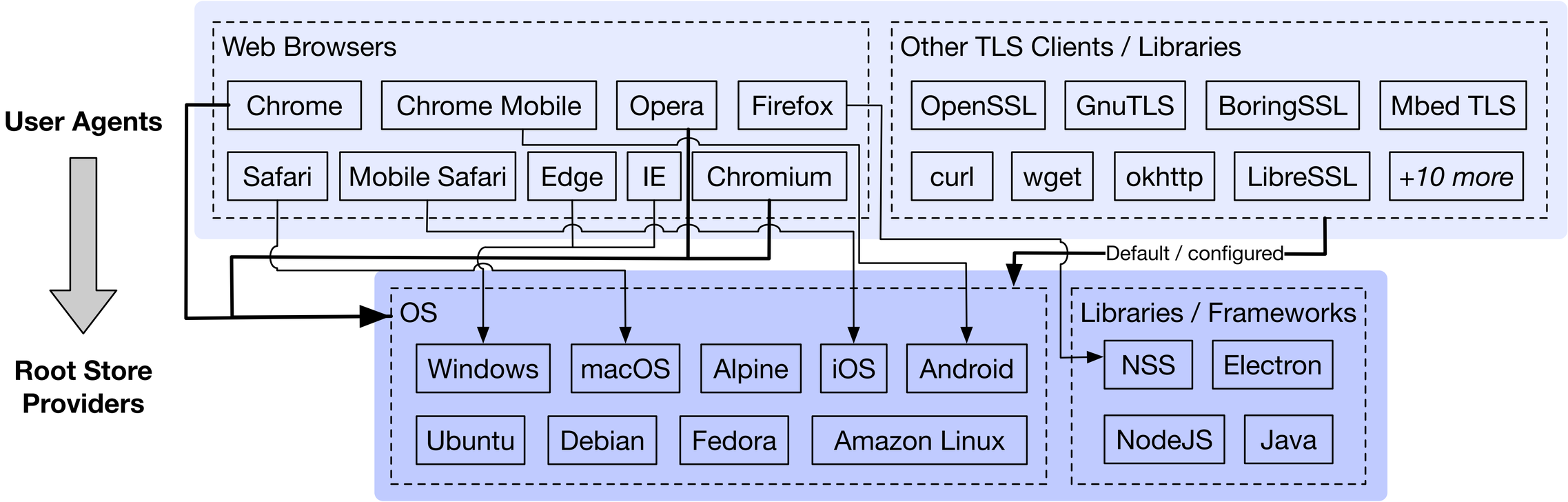
Other TLS Clients / Libraries

- OpenSSL
- GnuTLS
- BoringSSL
- Mbed TLS
- curl
- wget
- okhttp
- LibreSSL
- *+10 more*

Collected root stores for 83% of global CDN top 200 user agents

Determined default root store for dozens of libraries / TLS clients

Root store providers



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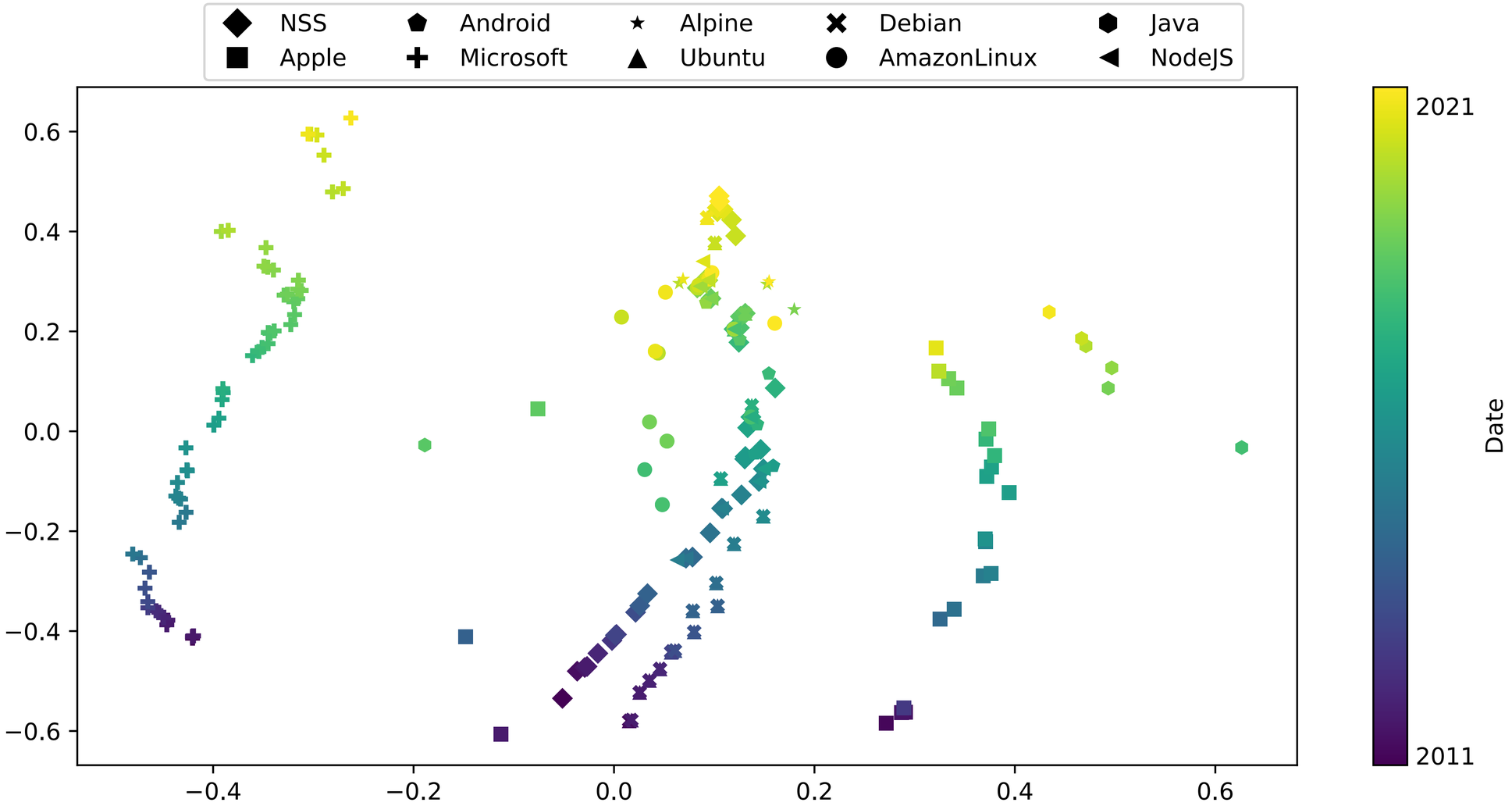
Clustering providers

metric MDS



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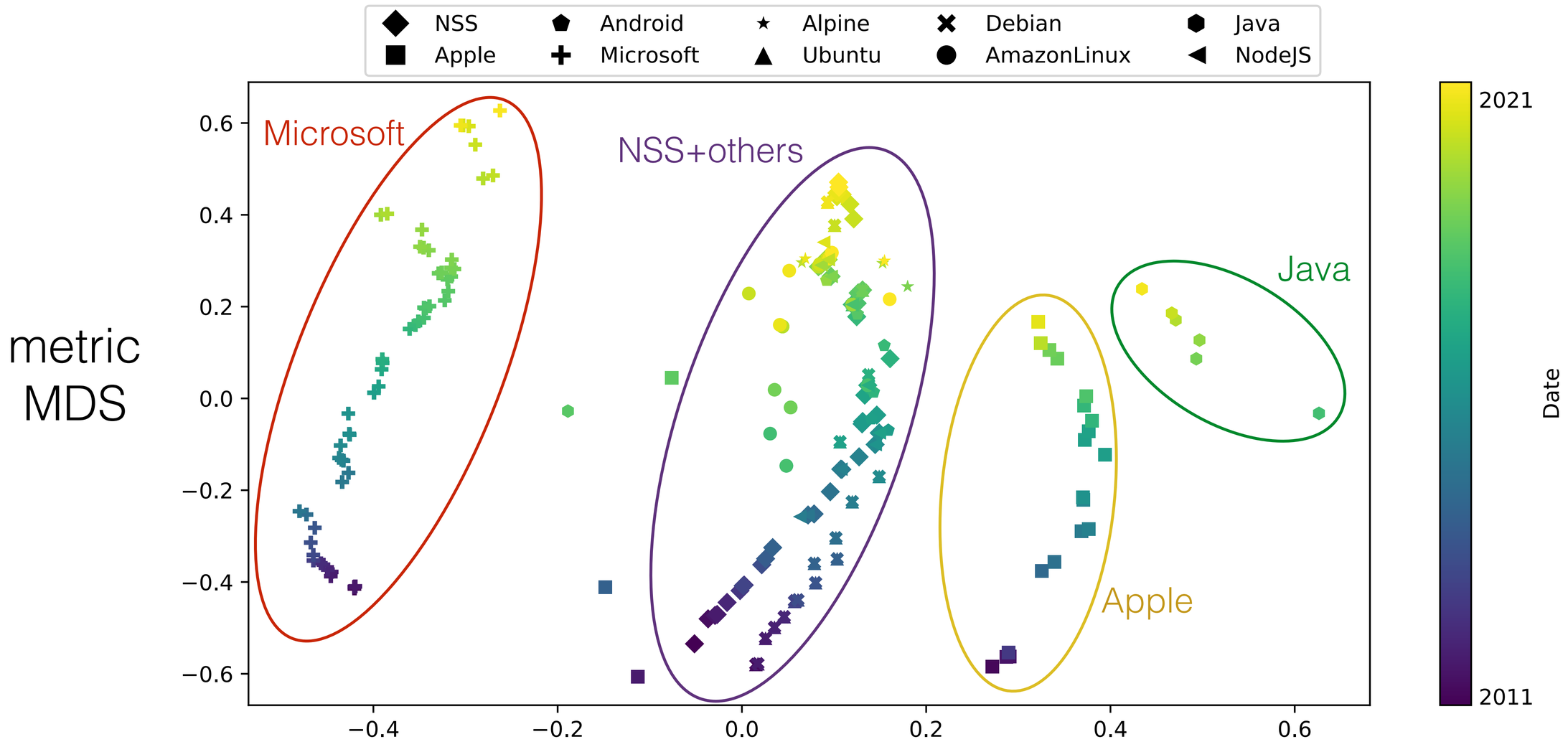

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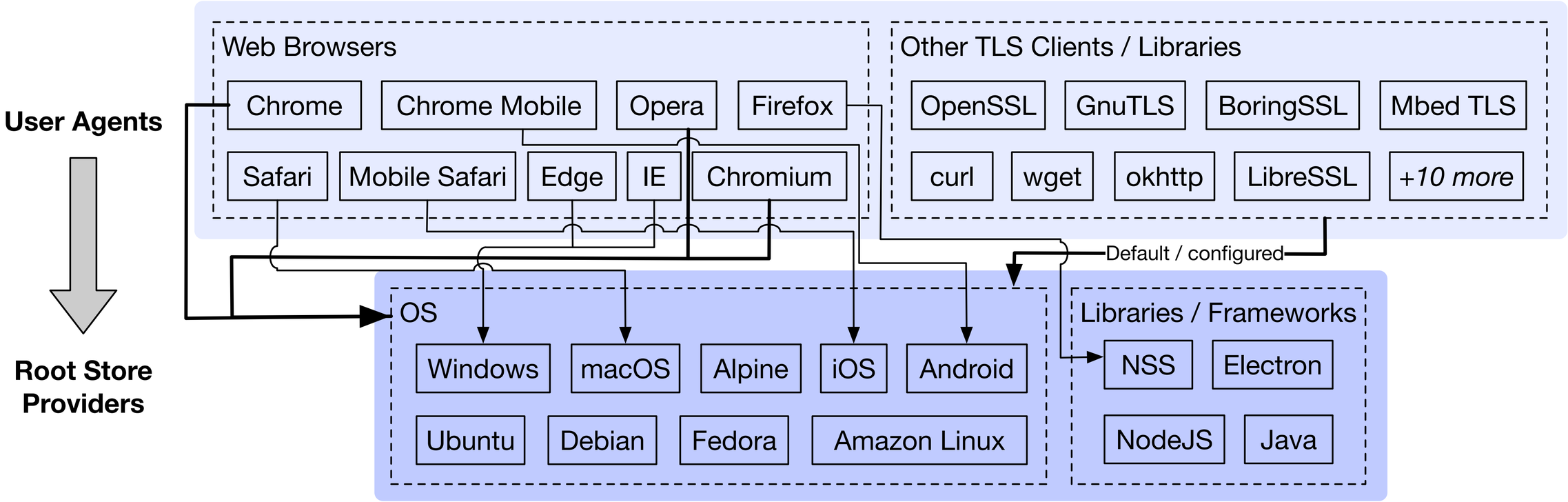
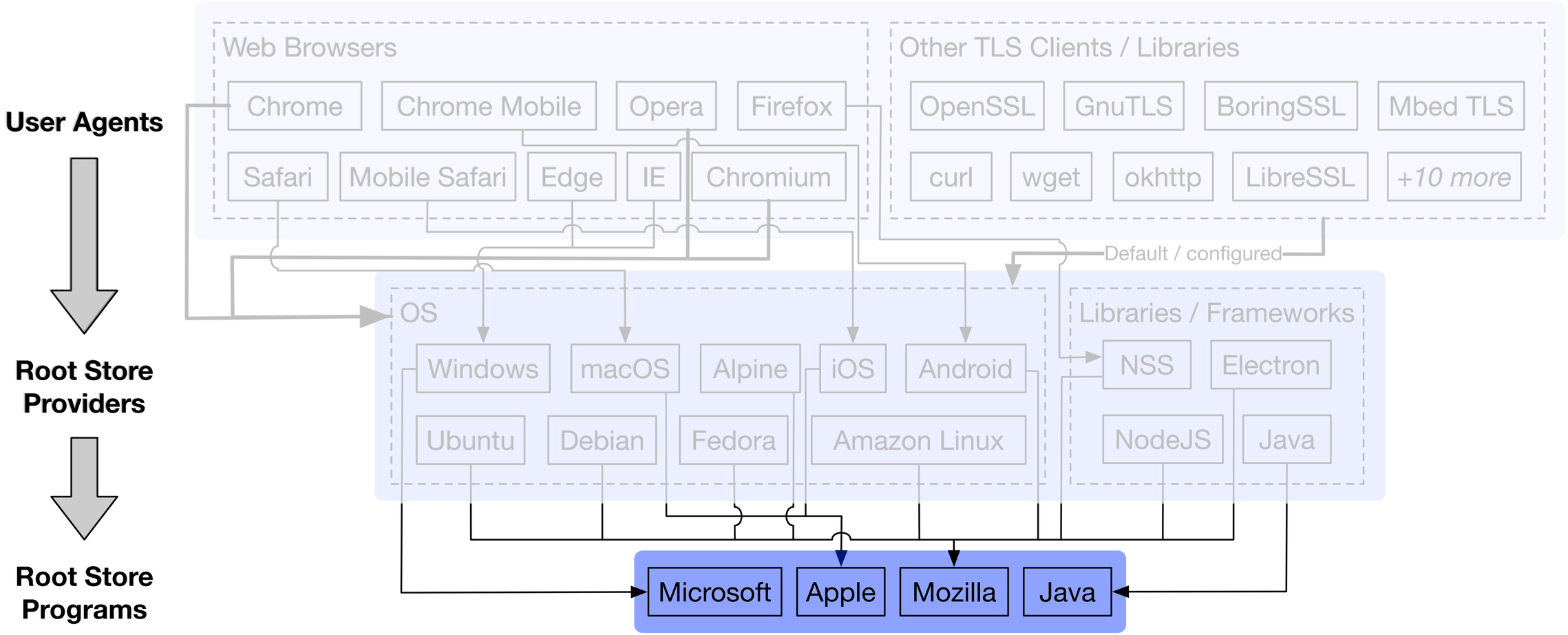


Root store programs



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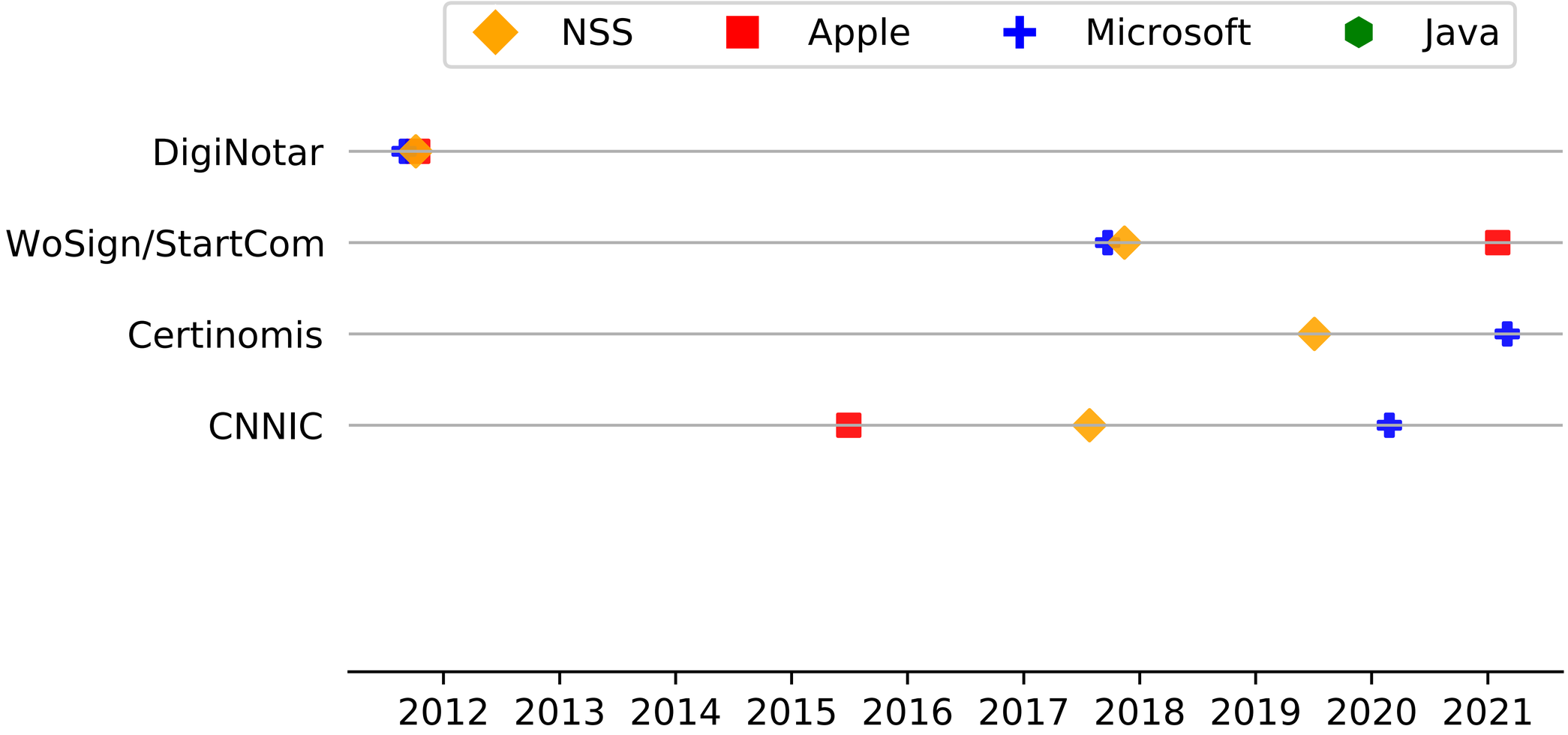
Root program comparison



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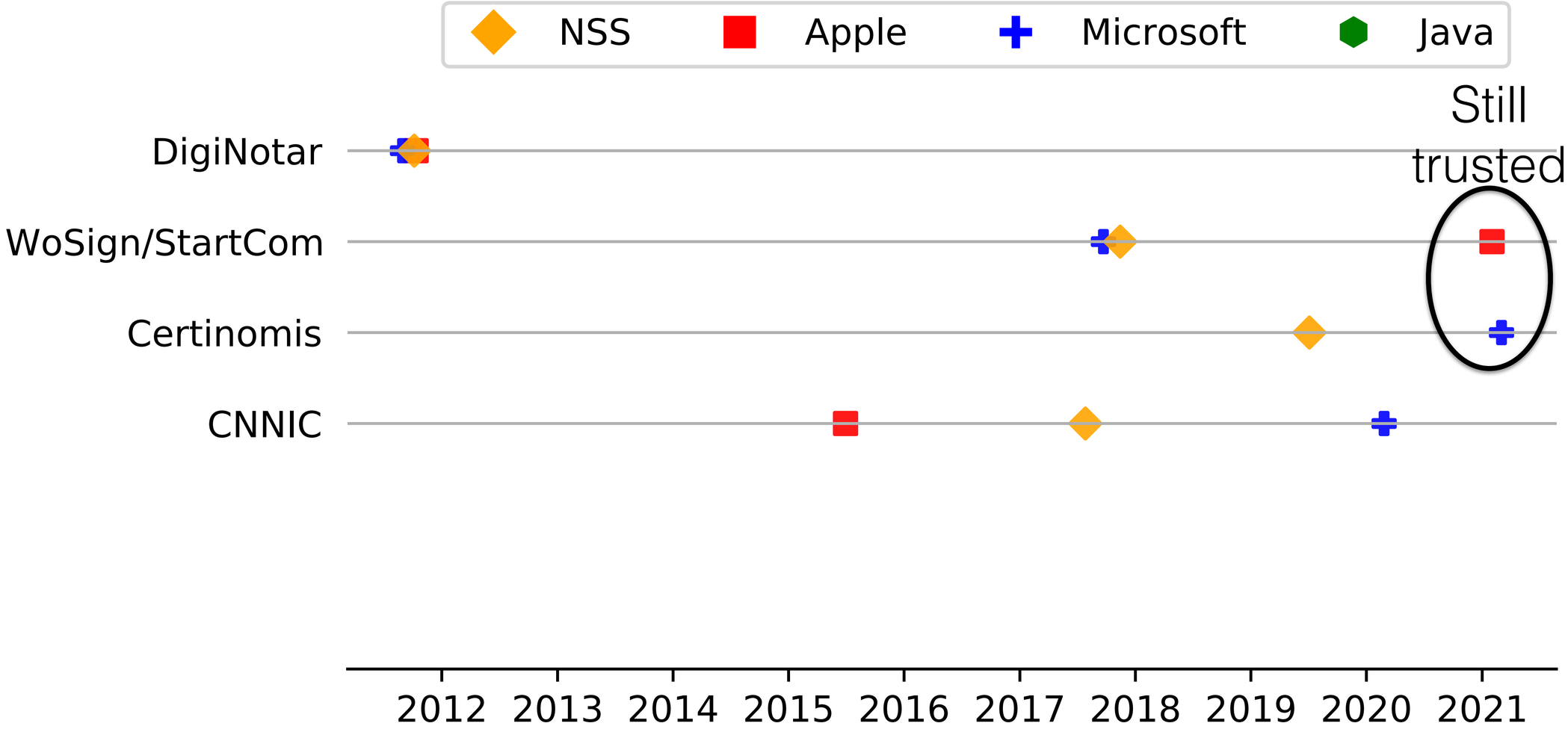

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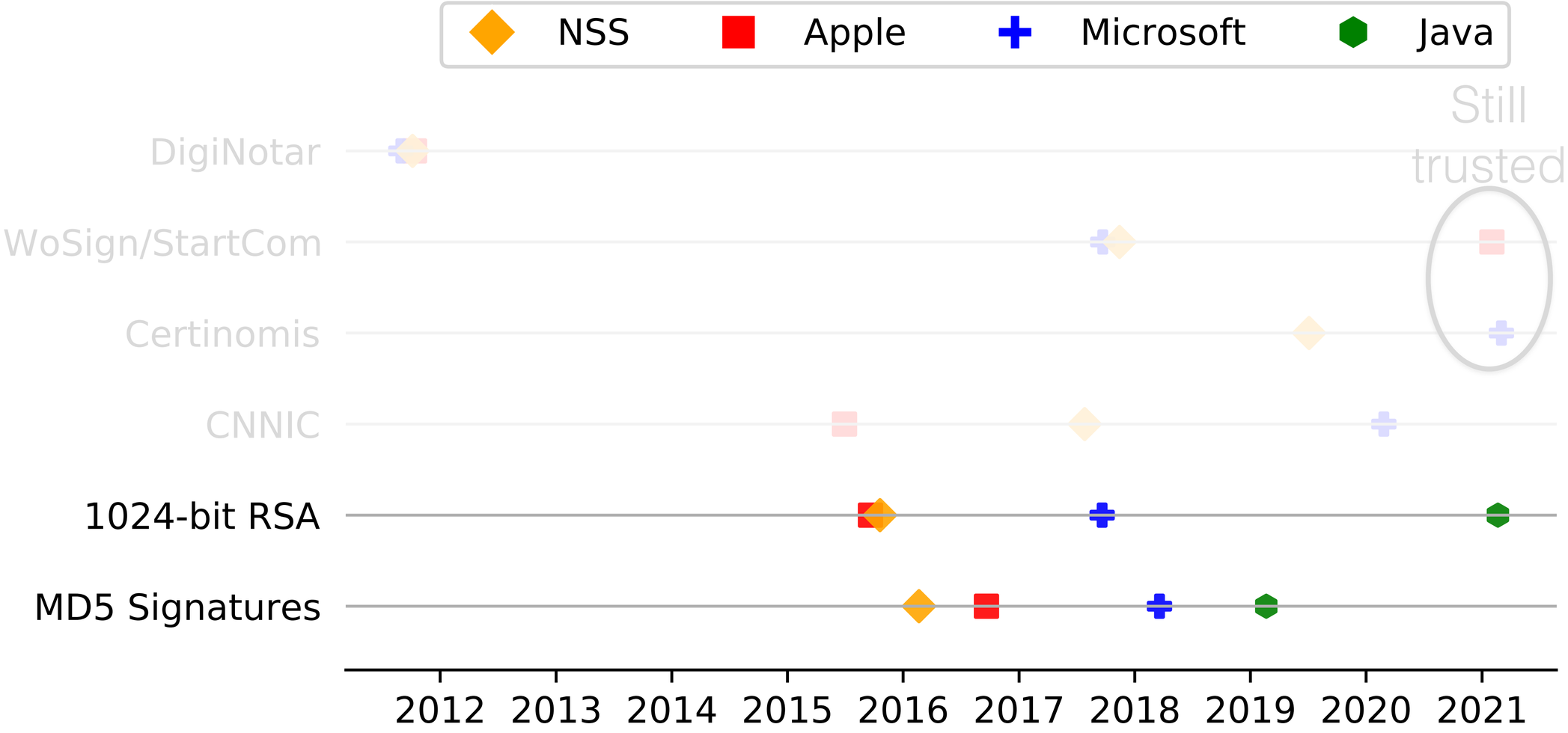

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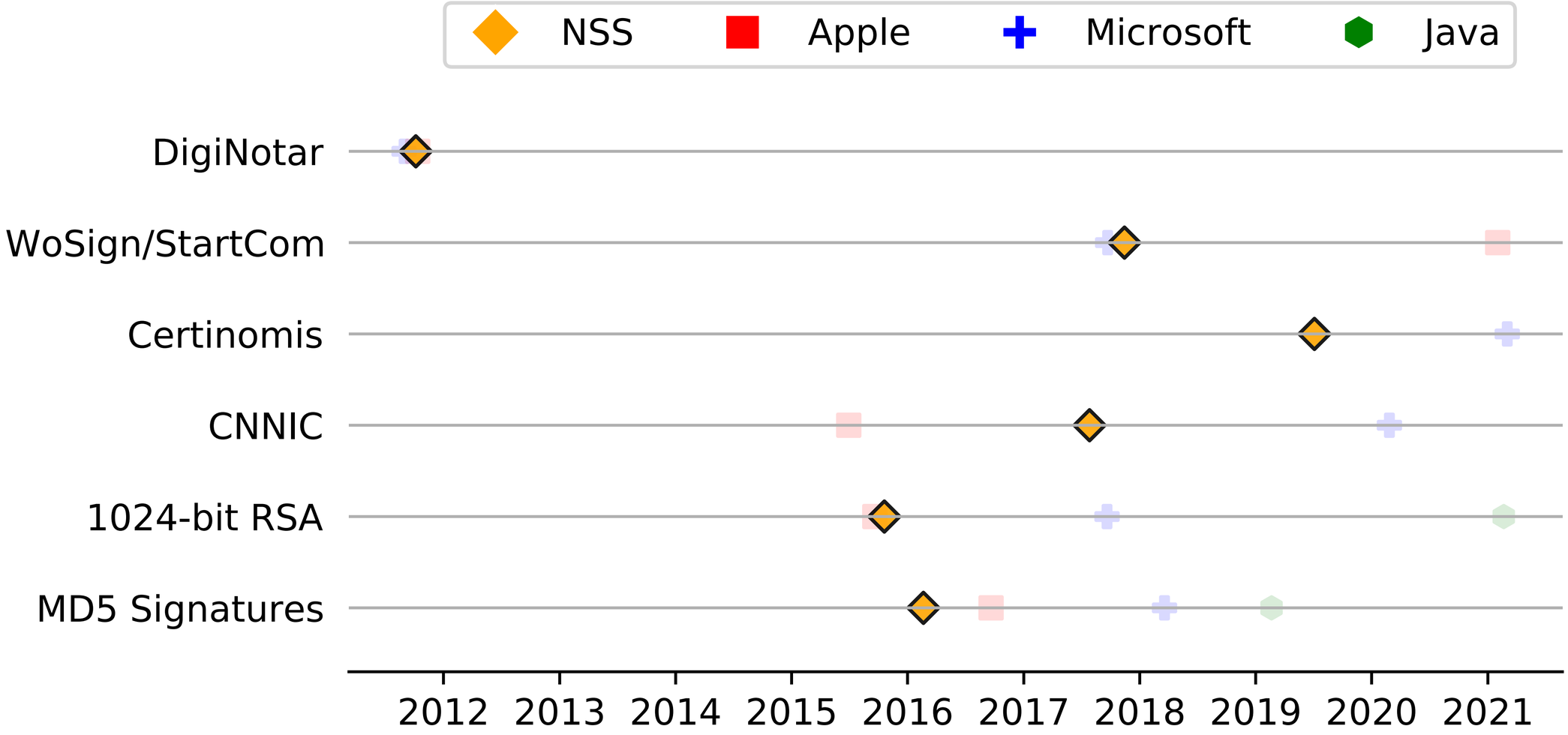

Root program comparison

1. Mozilla responds quickly to CA distrust incidents; Microsoft relatively slow, Apple varies.

2. Apple/Mozilla operate relatively hygienic root stores.

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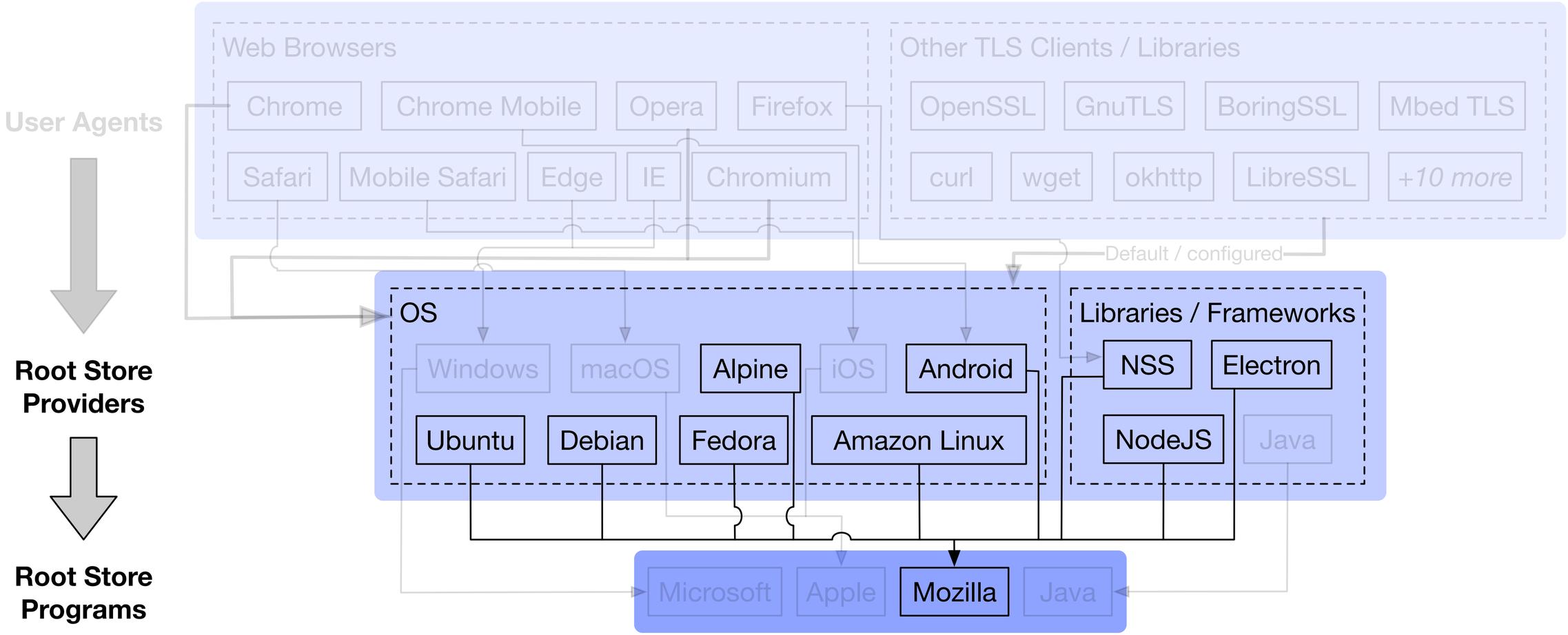
2. Apple/Mozilla operate relatively hygienic root stores.

3. Size: Mozilla < Apple < Microsoft; Mozilla most restrictive, Microsoft allows government super-CAs.

4. Mozilla runs the most transparent root store program.

Mozilla derivatives



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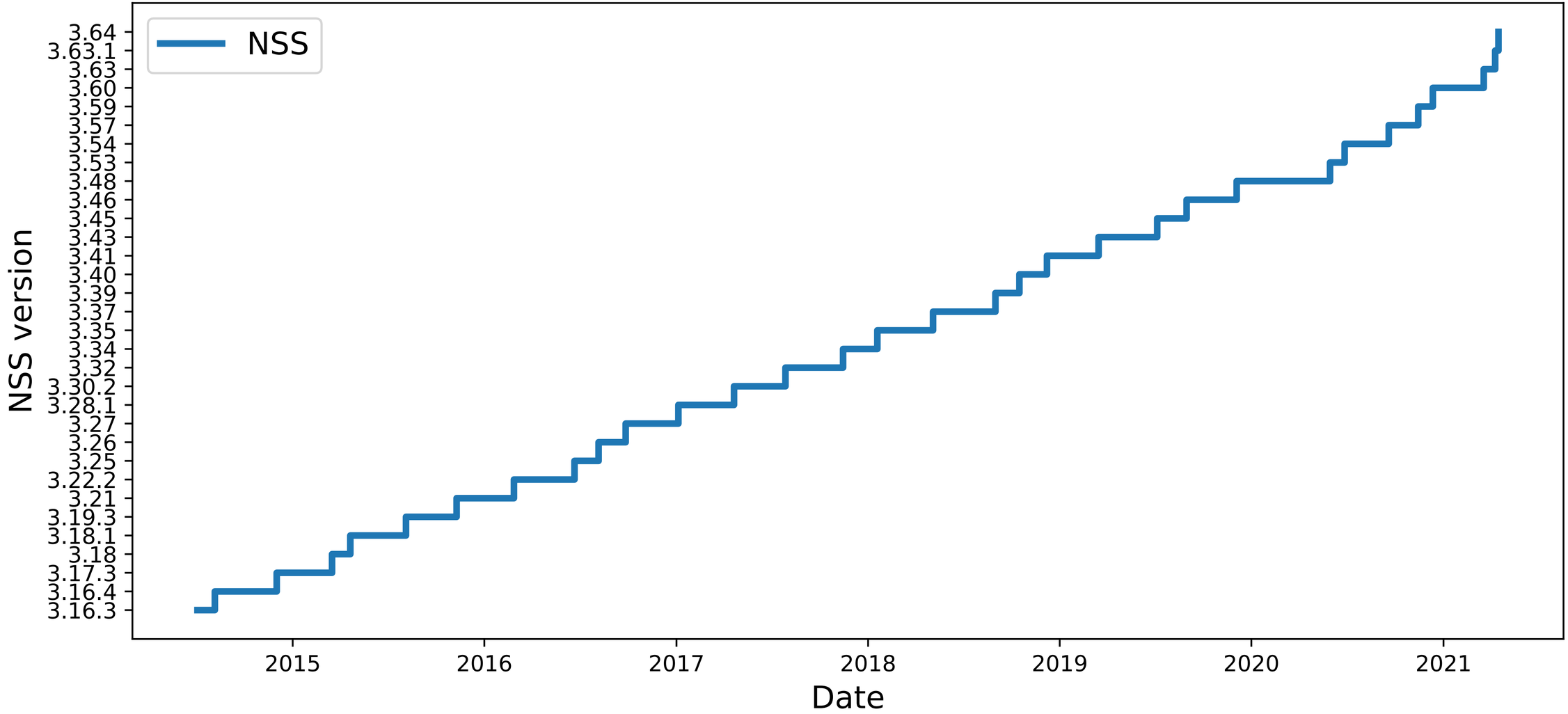
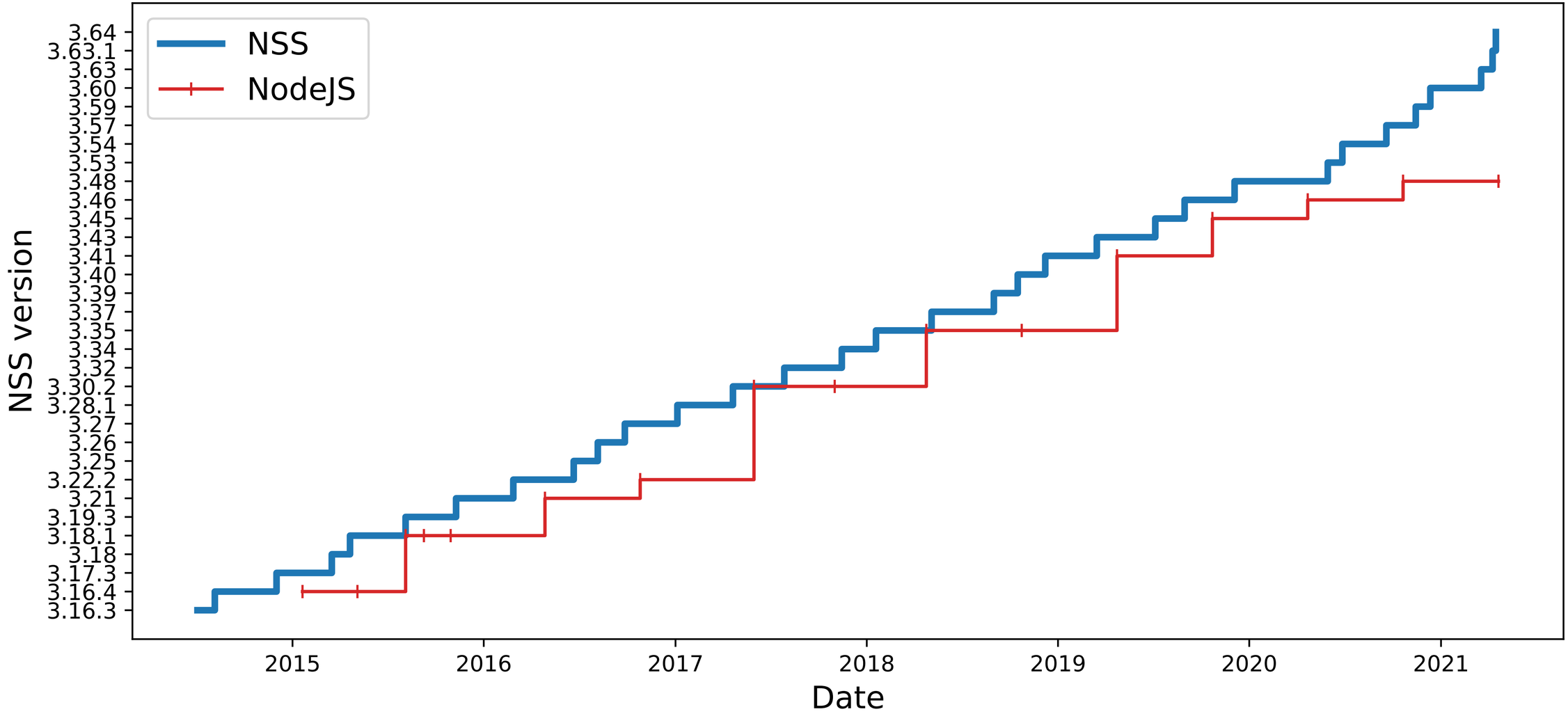
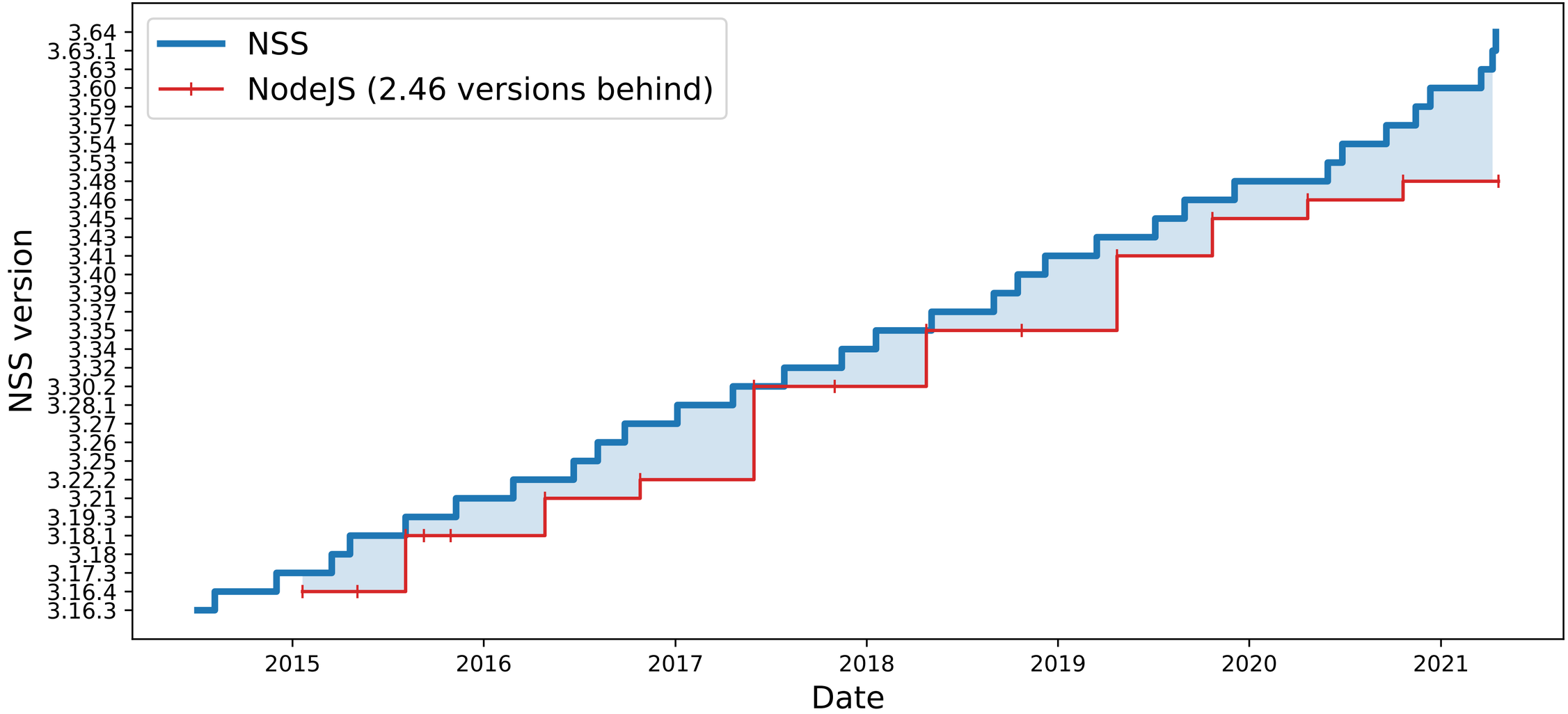
Derivative delay



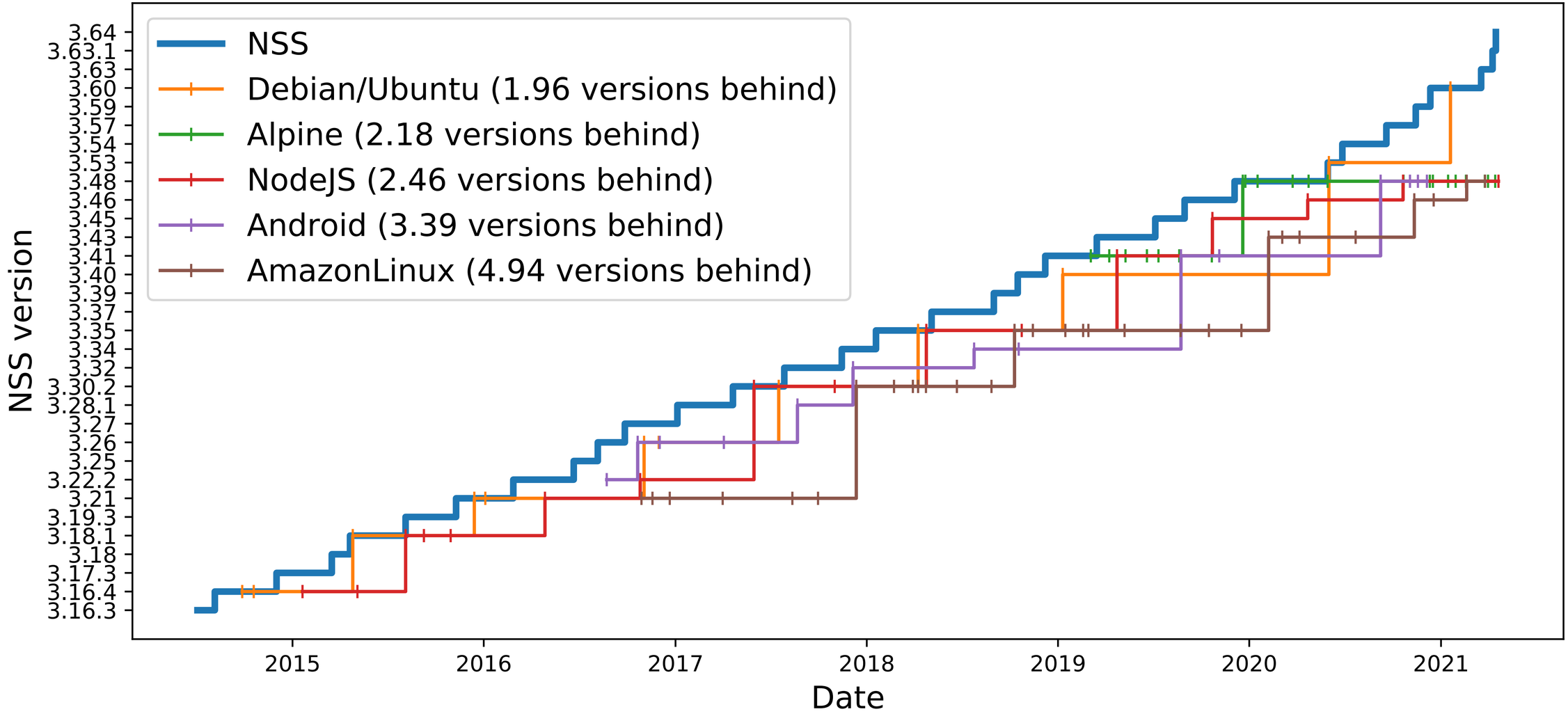
Derivative delay



Derivative delay



Derivative delay



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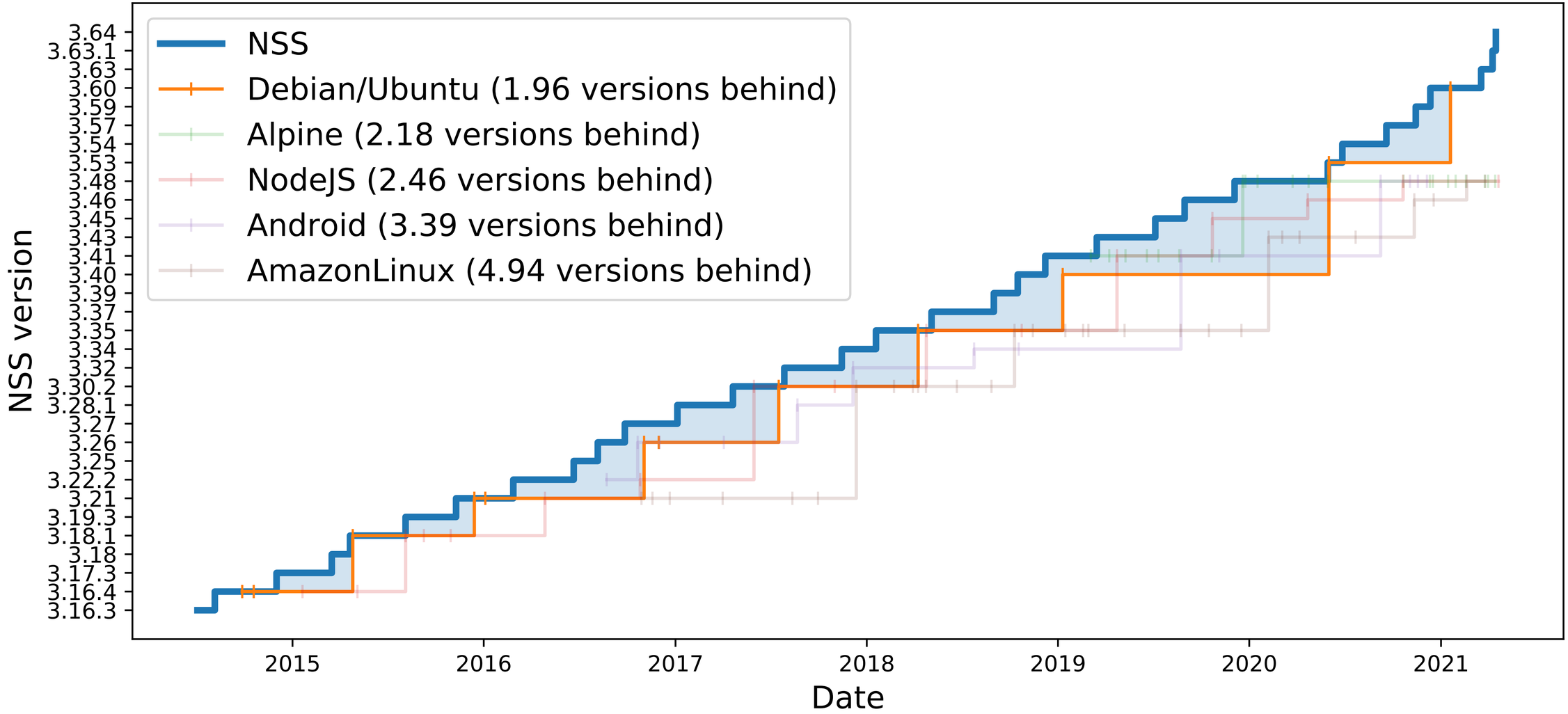

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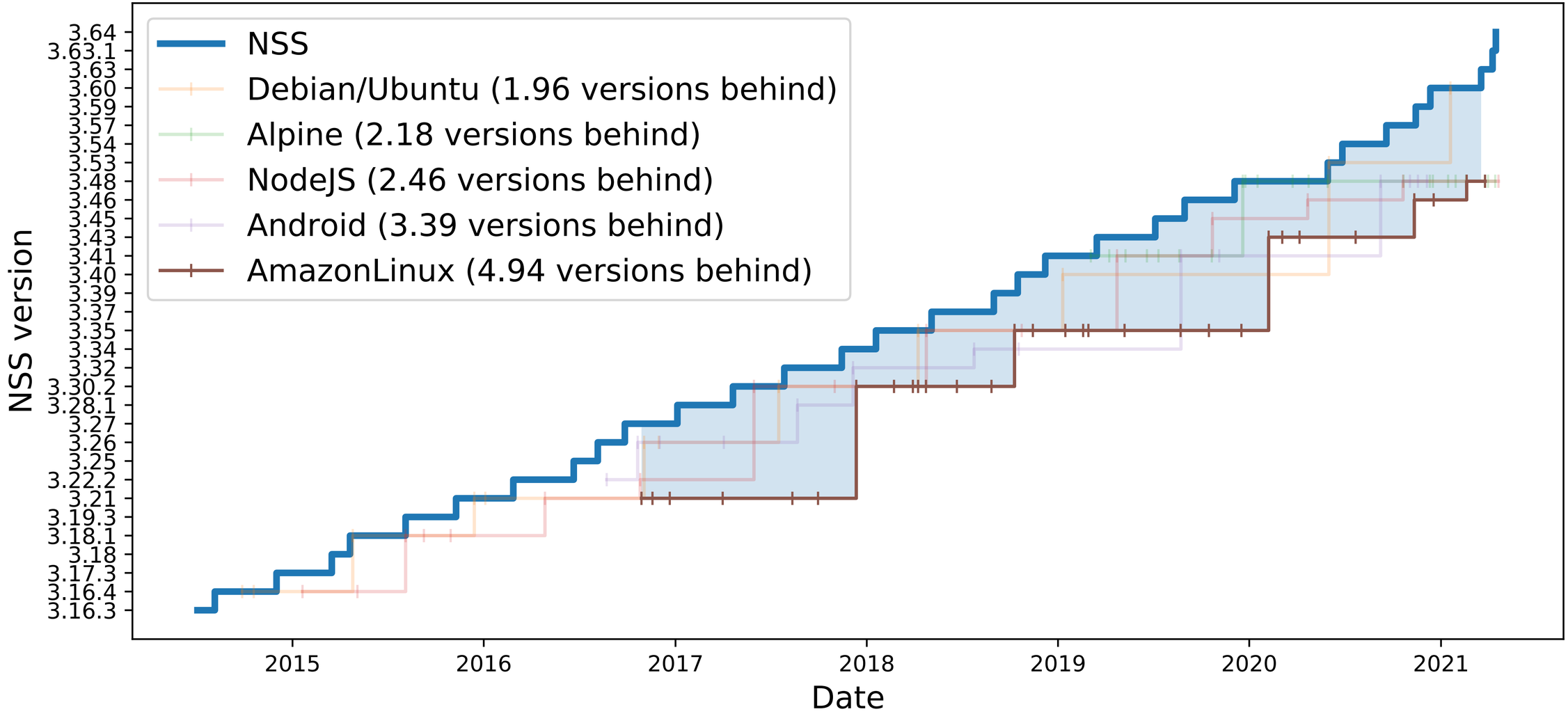
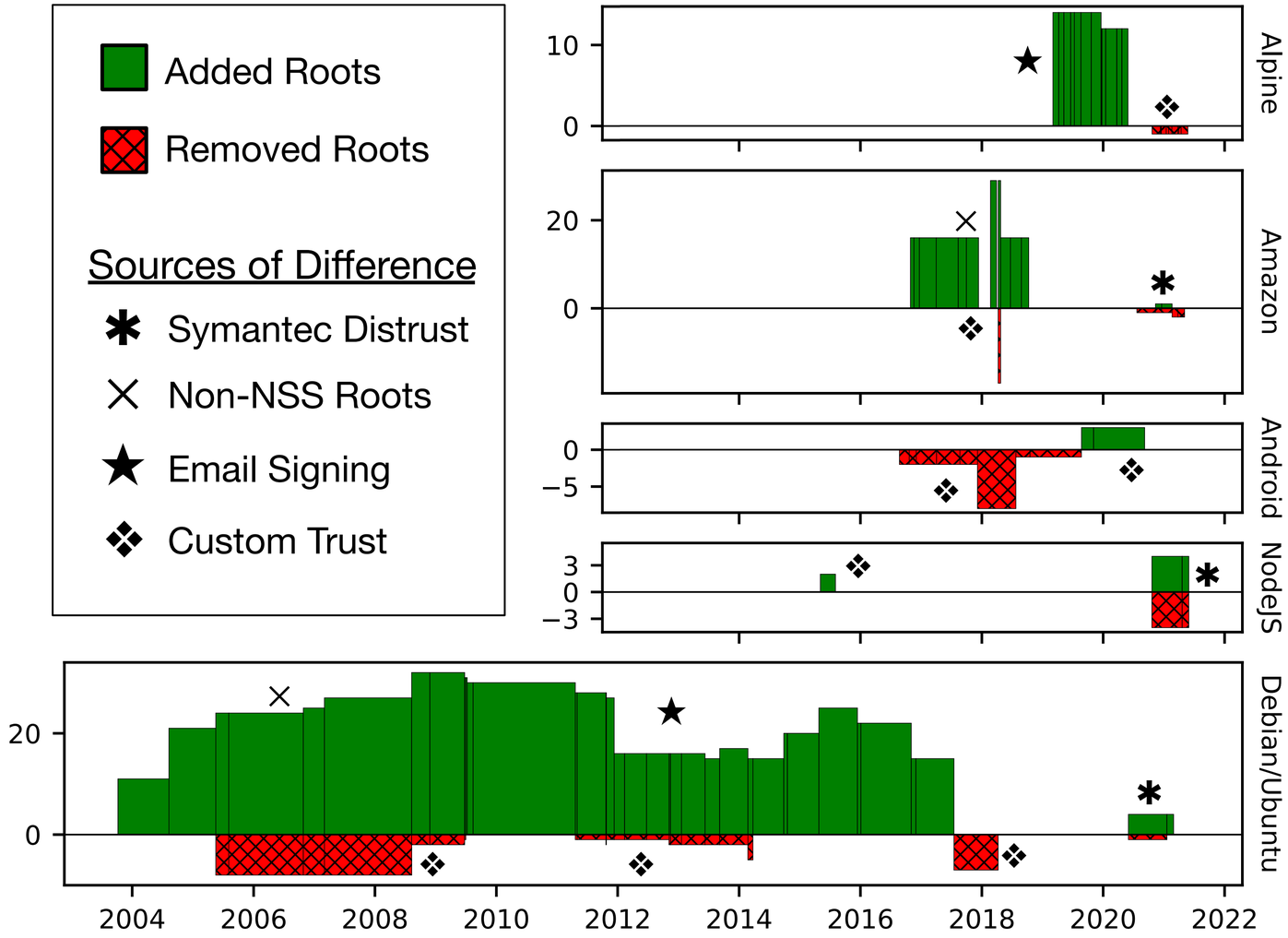


Trust deviations



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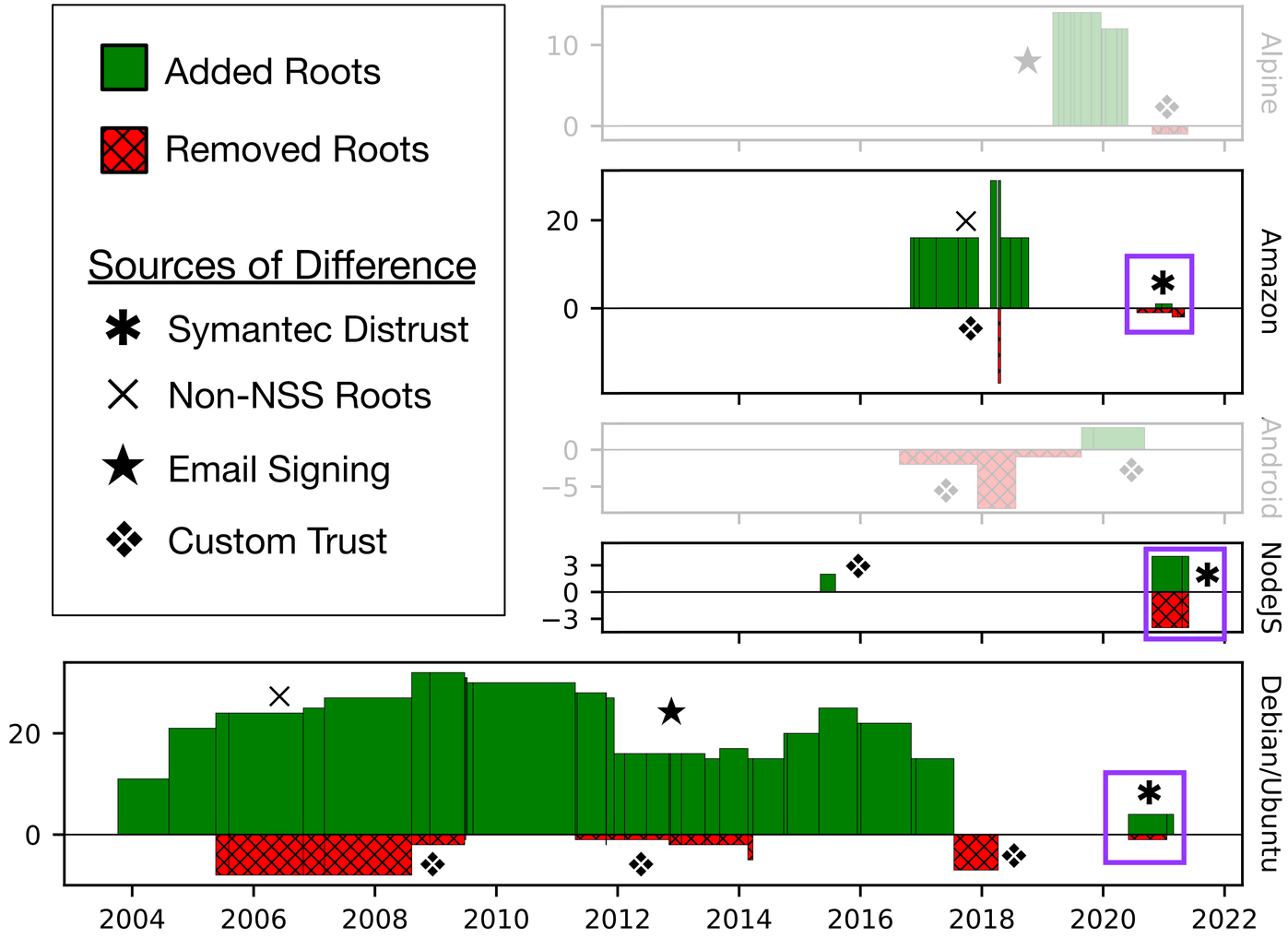

Trust purpose conflation: trusting non-TLS certificates

Partial trust incapability: Symantec distrust dilemma

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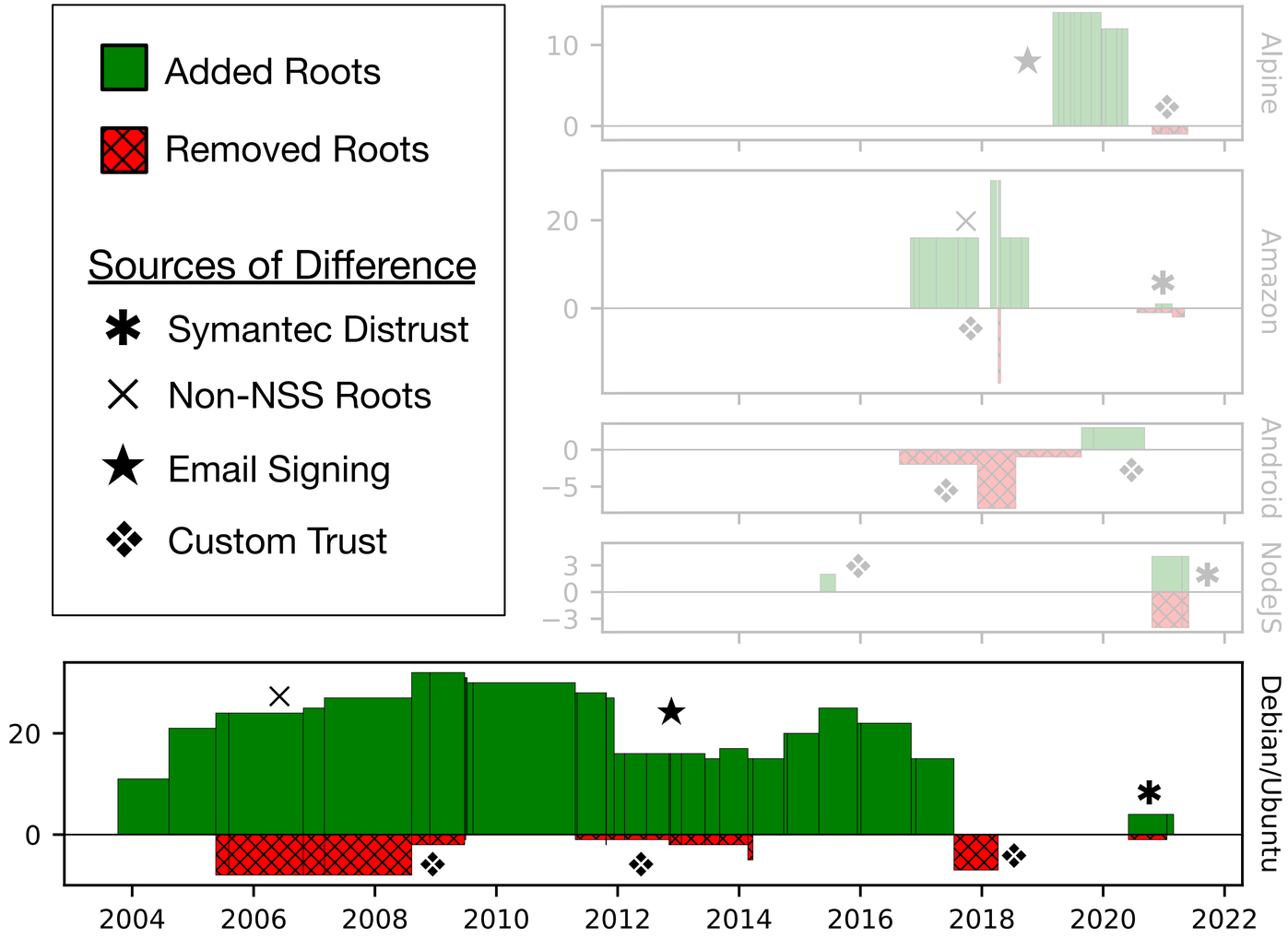

Trust purpose conflation: trusting non-TLS certificates

Partial trust incapability: Symantec distrust dilemma

Non-NSS trusted CAs: questionable trust

App. developer confusion: trusting CAs for code signing, timestamping

Summary

Popular TLS user agents infrequently make their own TLS trust decisions and rely on the OS.

Apple, Microsoft run major root programs; all other root providers originate from Mozilla's NSS root program.

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NSS derivatives copy poorly: delayed updates, questionable bespoke trust, incompatible trust scope.

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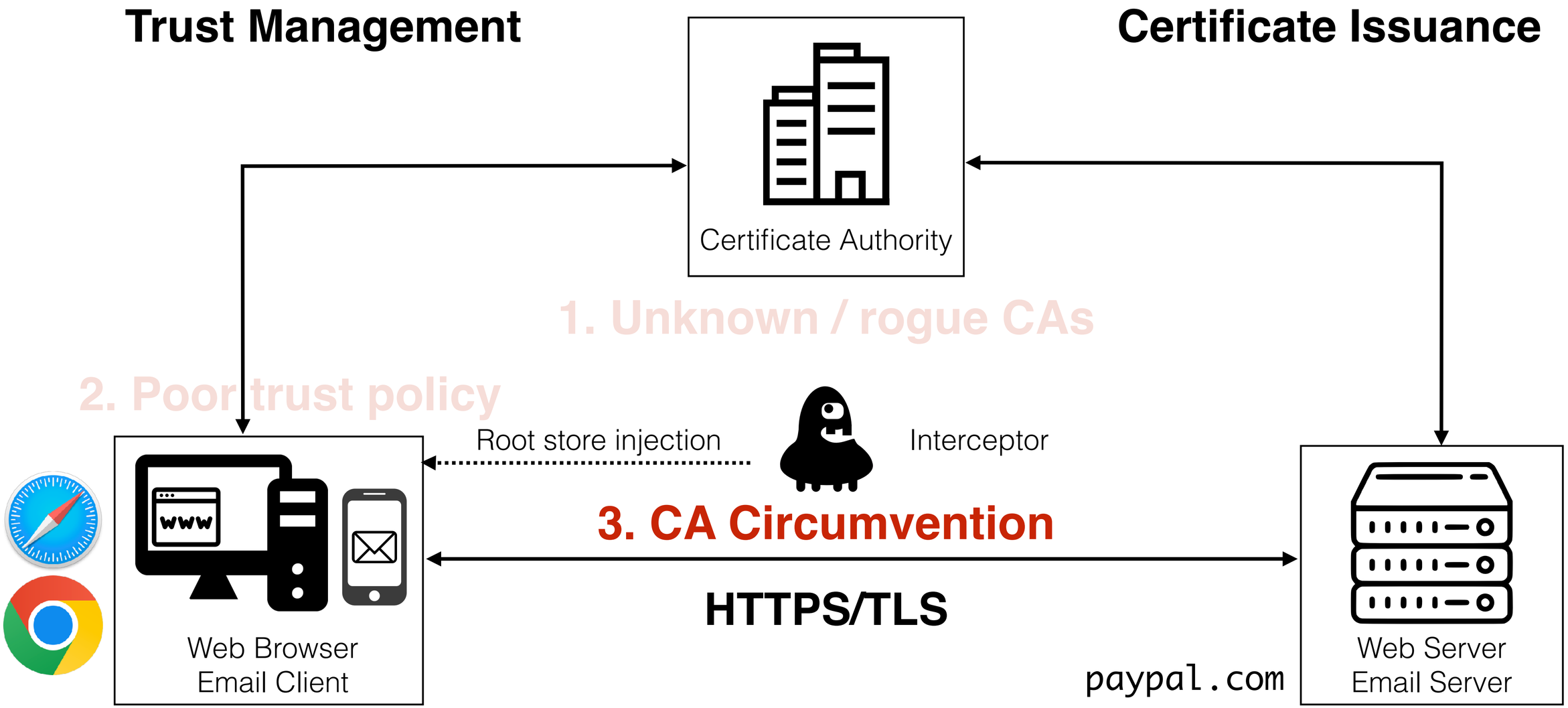
Popular TLS user agents infrequently make their own TLS trust decisions and rely on the OS.

Apple, Microsoft run major root programs; all other root providers originate from Mozilla's NSS root program.

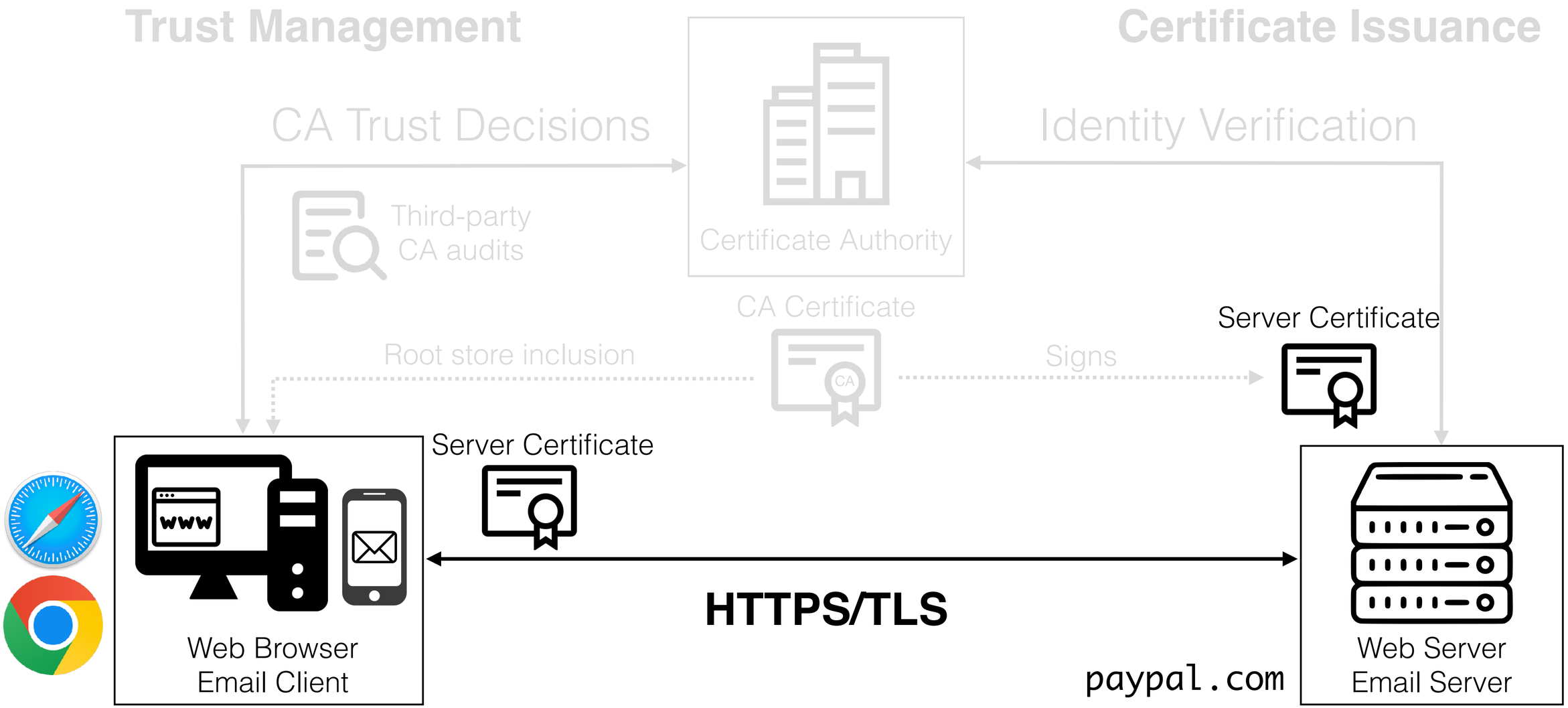
NSS derivatives copy poorly: delayed updates, questionable bespoke trust, incompatible trust scope.

Explicit provenance transparency and consistent trust schema would reduce manual copying, spotlight questionable custom trust.

Roadmap

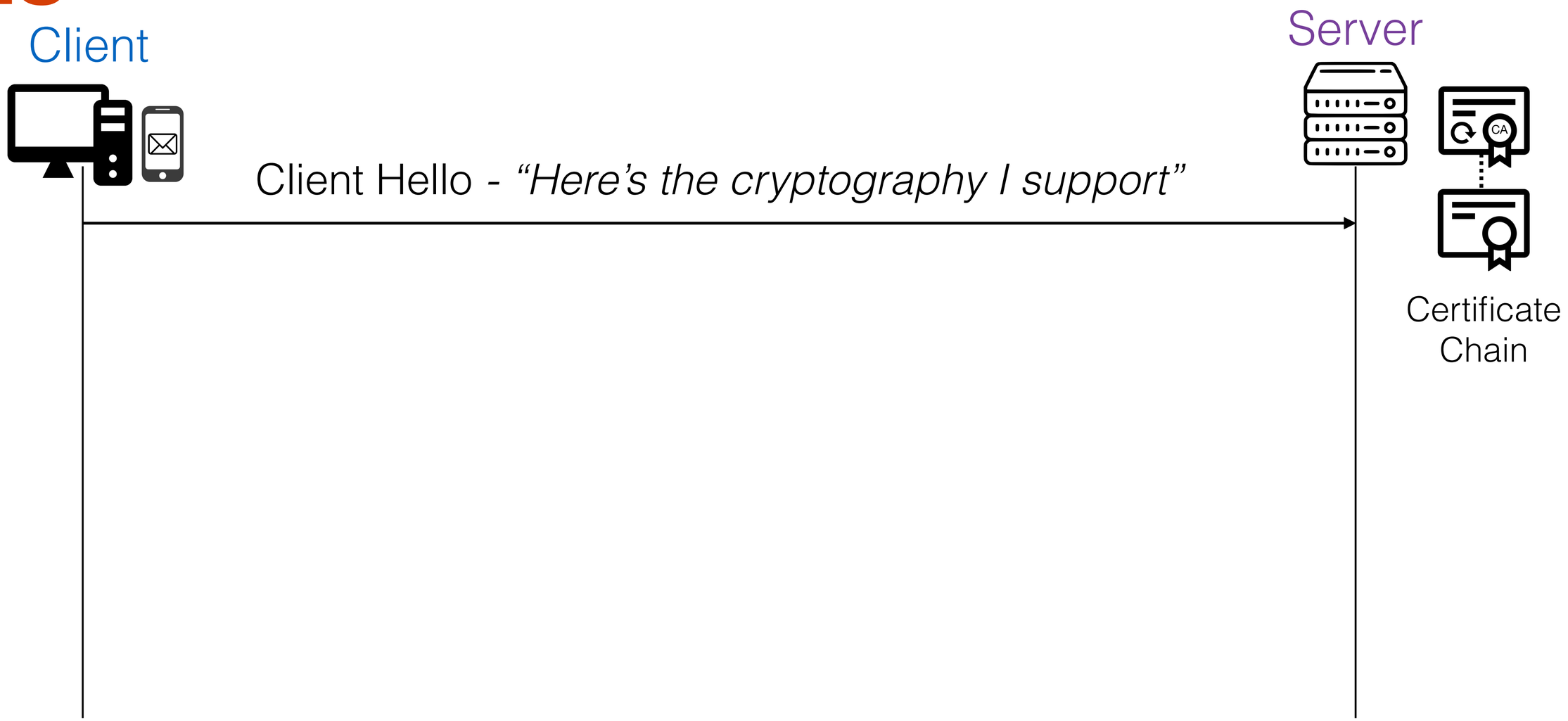

Trust Management
Certificate Issuance
Certificate Authority
1. Unknown / rogue CAs
2. Poor trust policy
Root store injection
Interceptor
3. CA Circumvention
HTTPS/TLS
Web Browser
Email Client
paypal.com
Web Server
Email Server

TLS

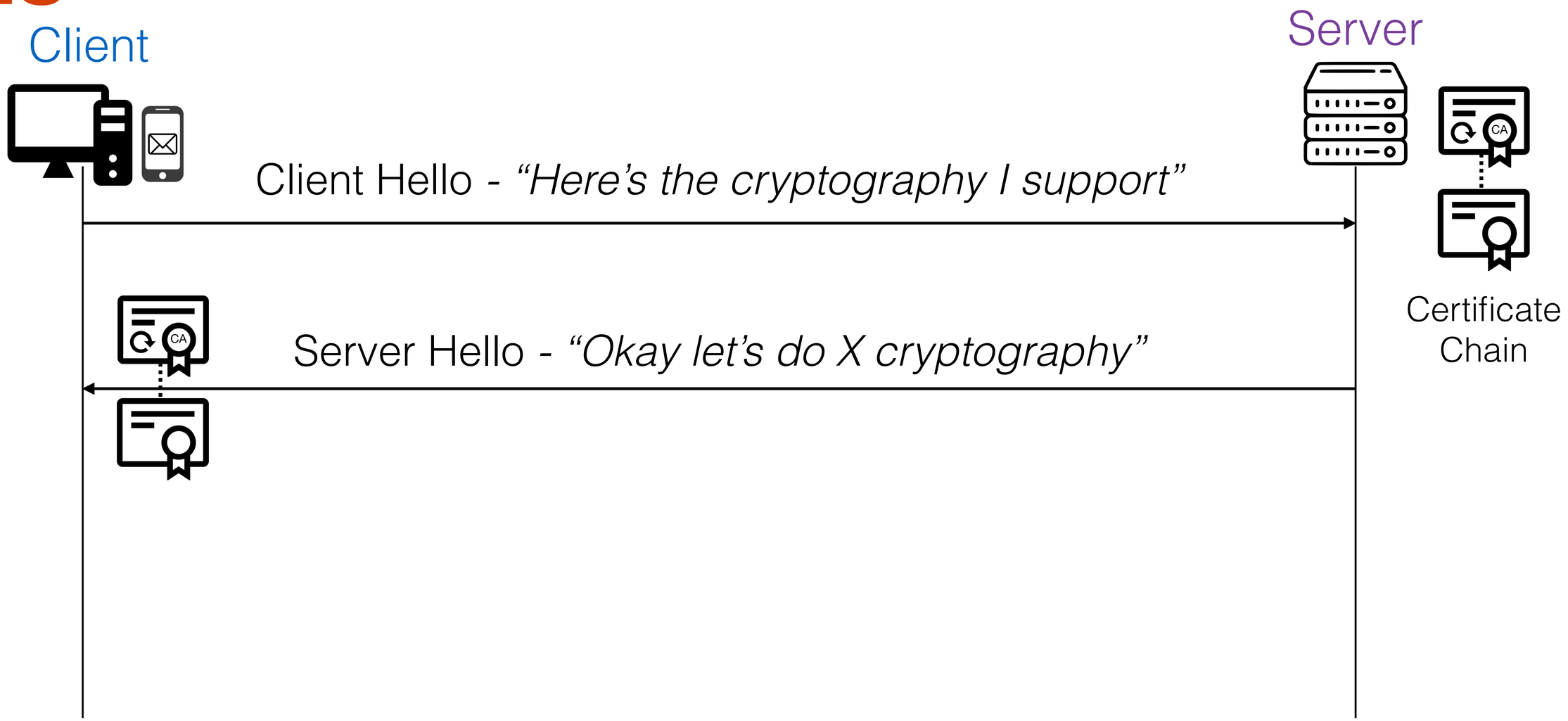

Trust Management
Certificate Issuance
CA Trust Decisions
Identity Verification
Third-party
CA audits
Certificate Authority
CA Certificate
Server Certificate
Root store inclusion
Signs
CA
Server Certificate
www
Web Browser
Email Client
HTTPS/TLS
paypal.com
Web Server
Email Server

TLS

TLS


Client
Server
Client Hello - *"Here's the cryptography I support"*
CA
Certificate Chain

TLS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Server Hello - *"Okay let's do X cryptography"*
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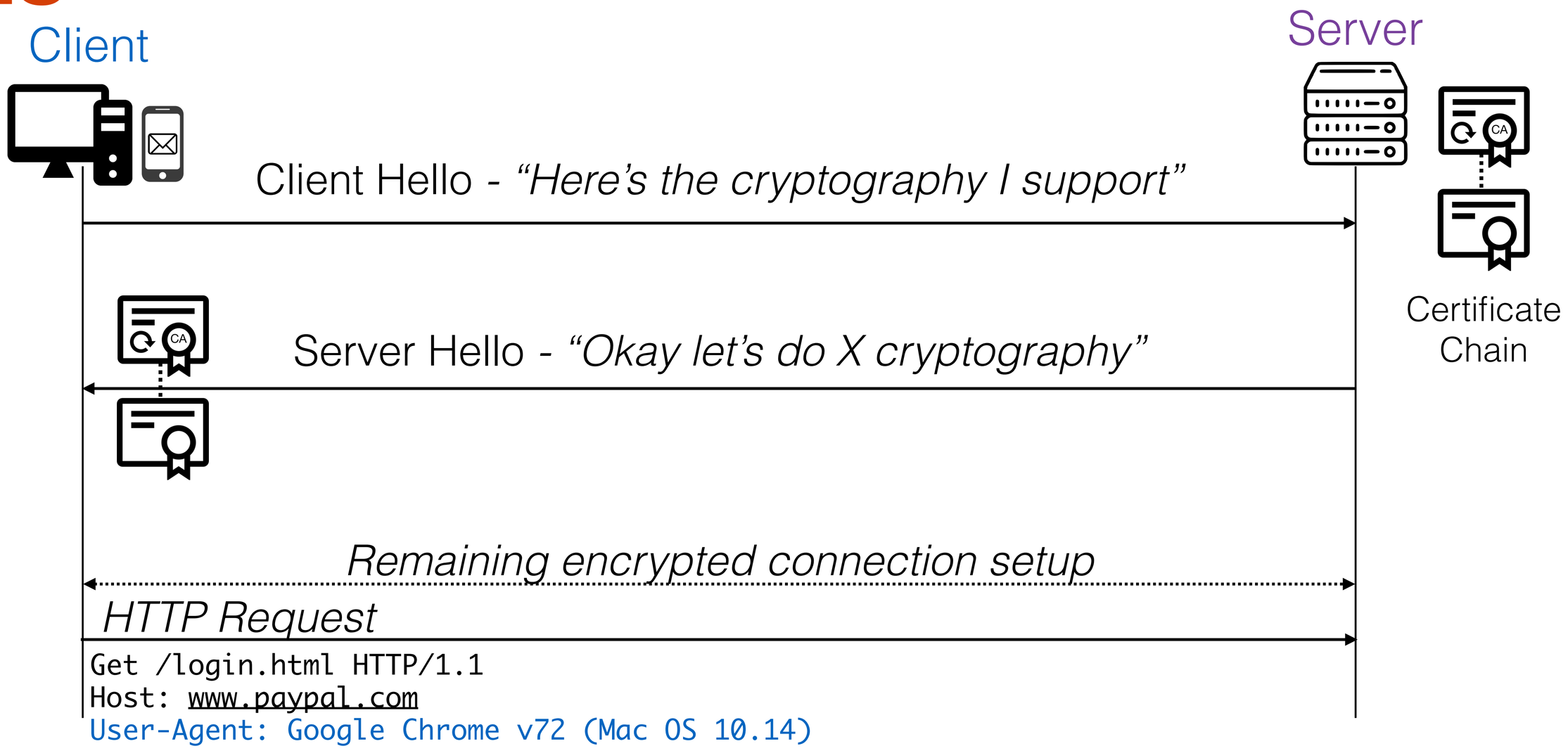
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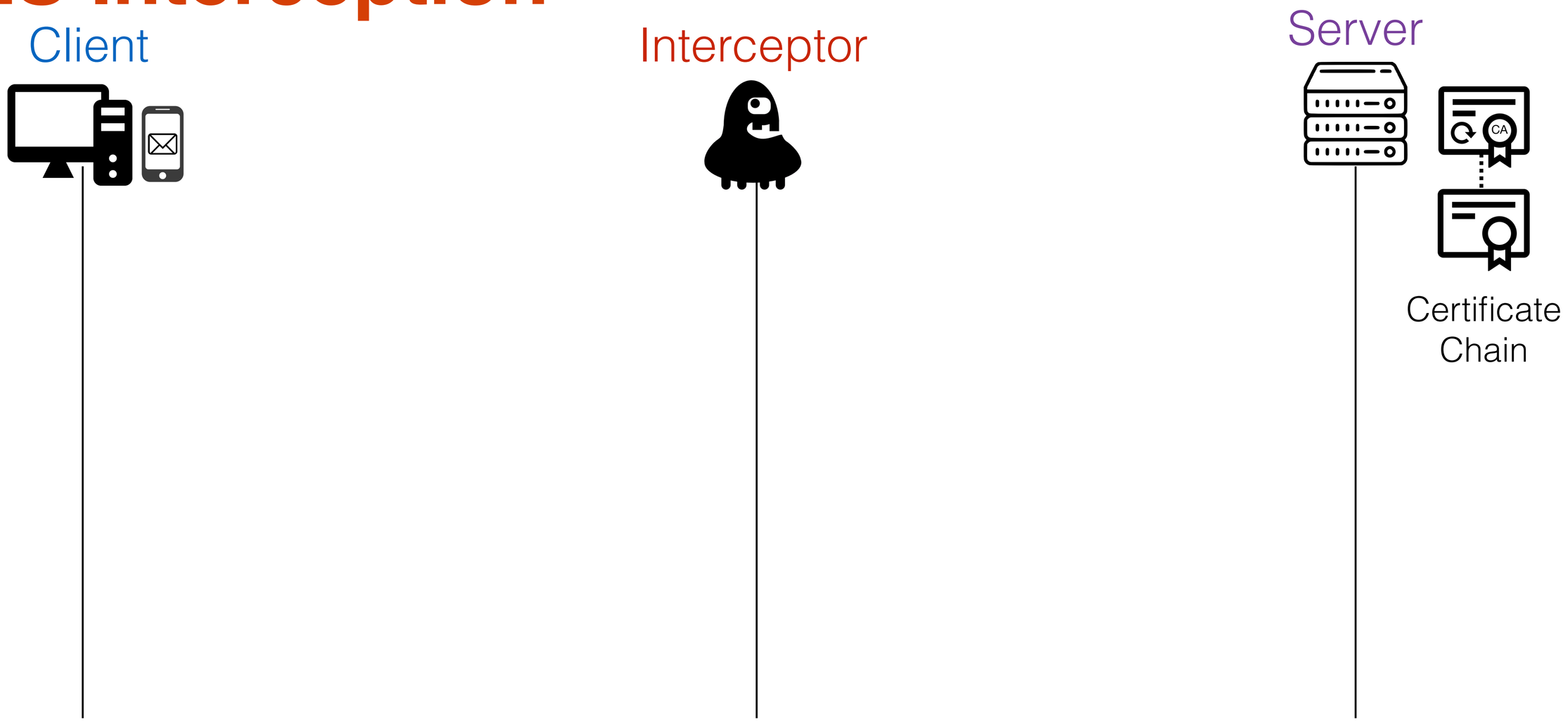
Remaining encrypted connection setup
HTTP Request
Get /login.html HTTP/1.1
Host: www.paypal.com
User-Agent: Google Chrome v72 (Mac OS 10.14)

TLS Interception



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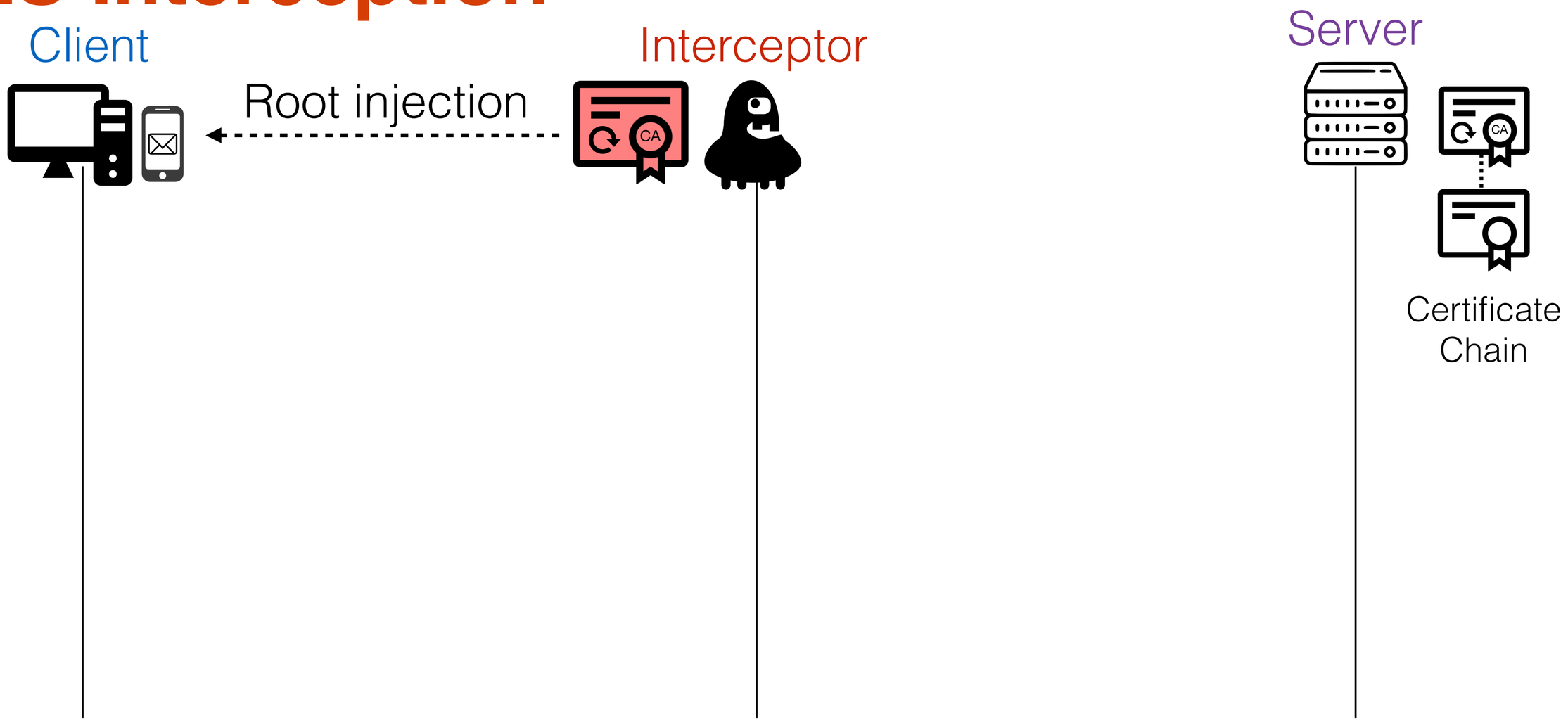

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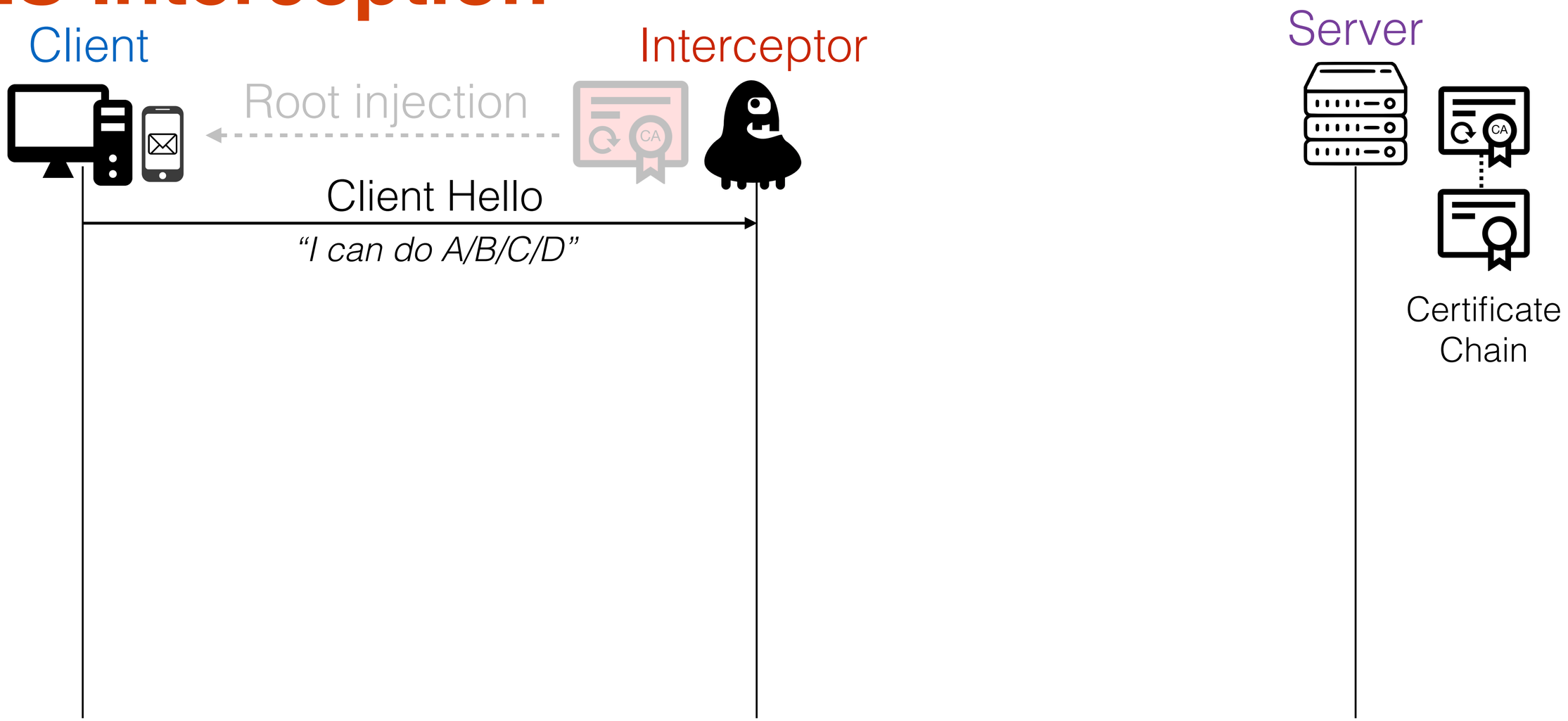

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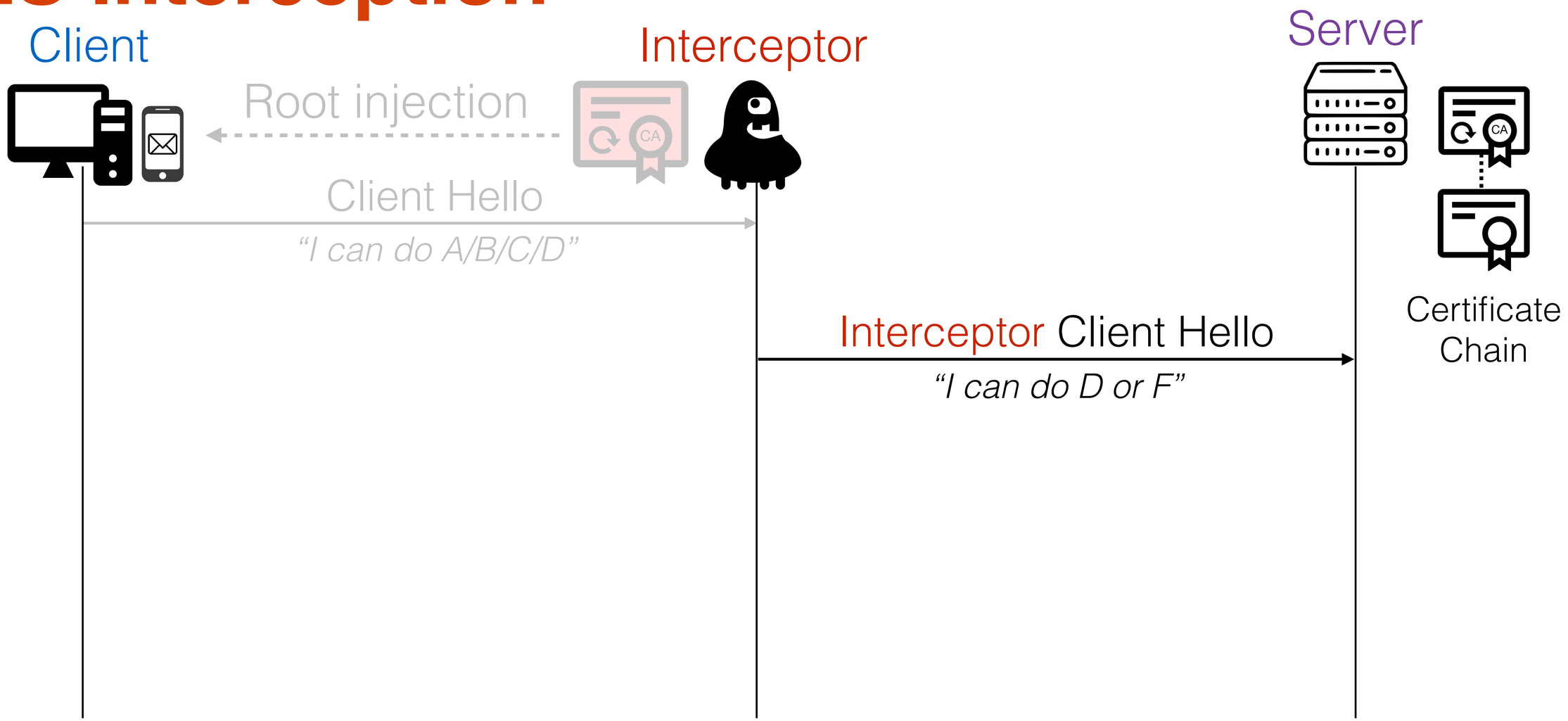

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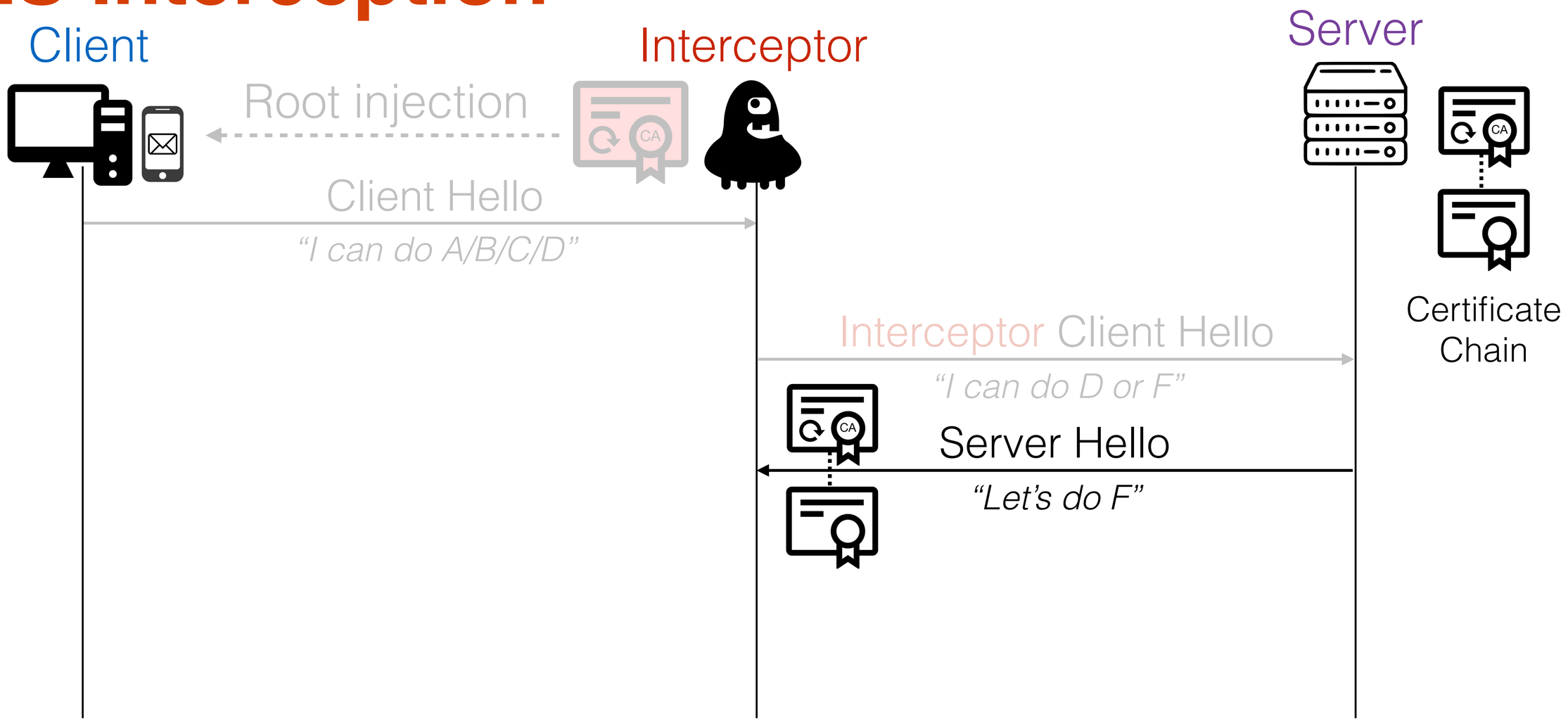

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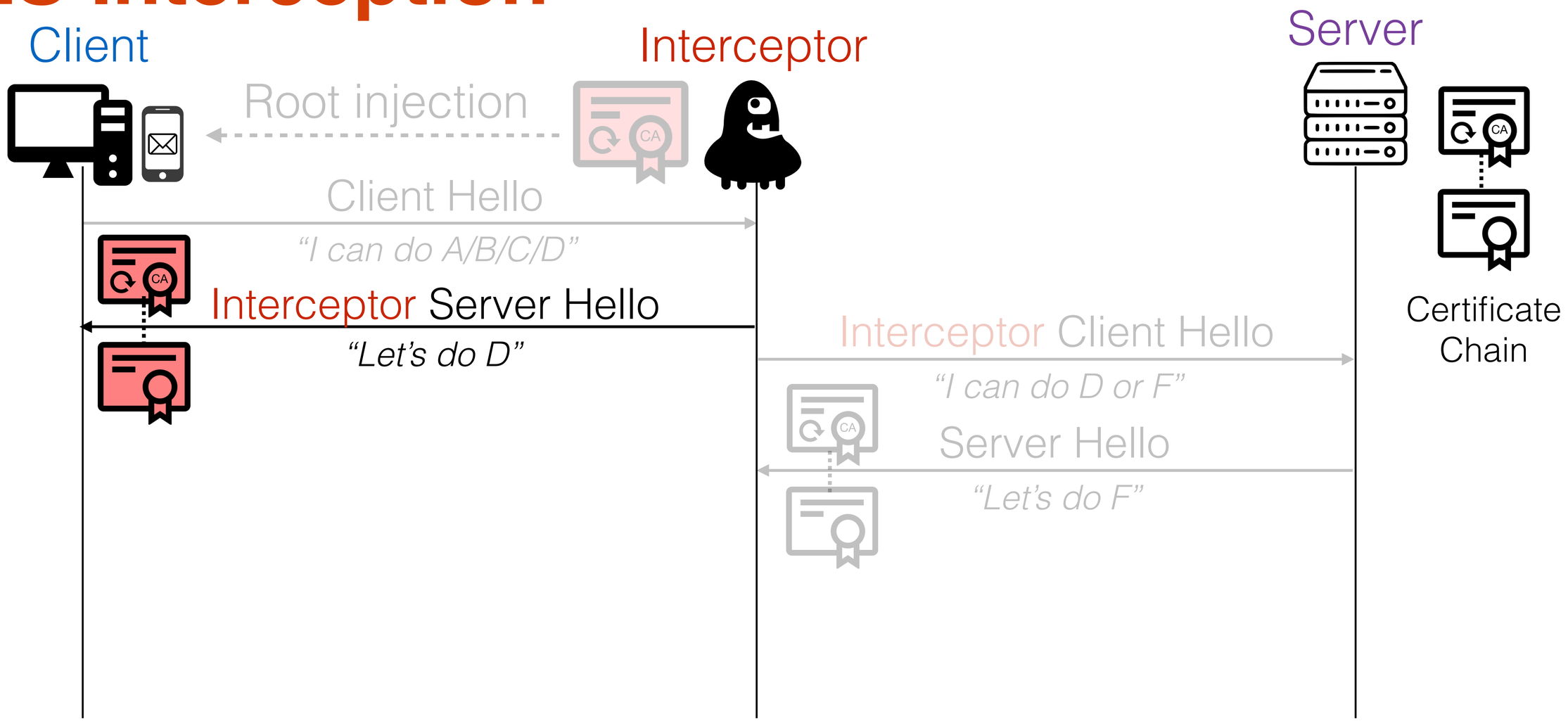

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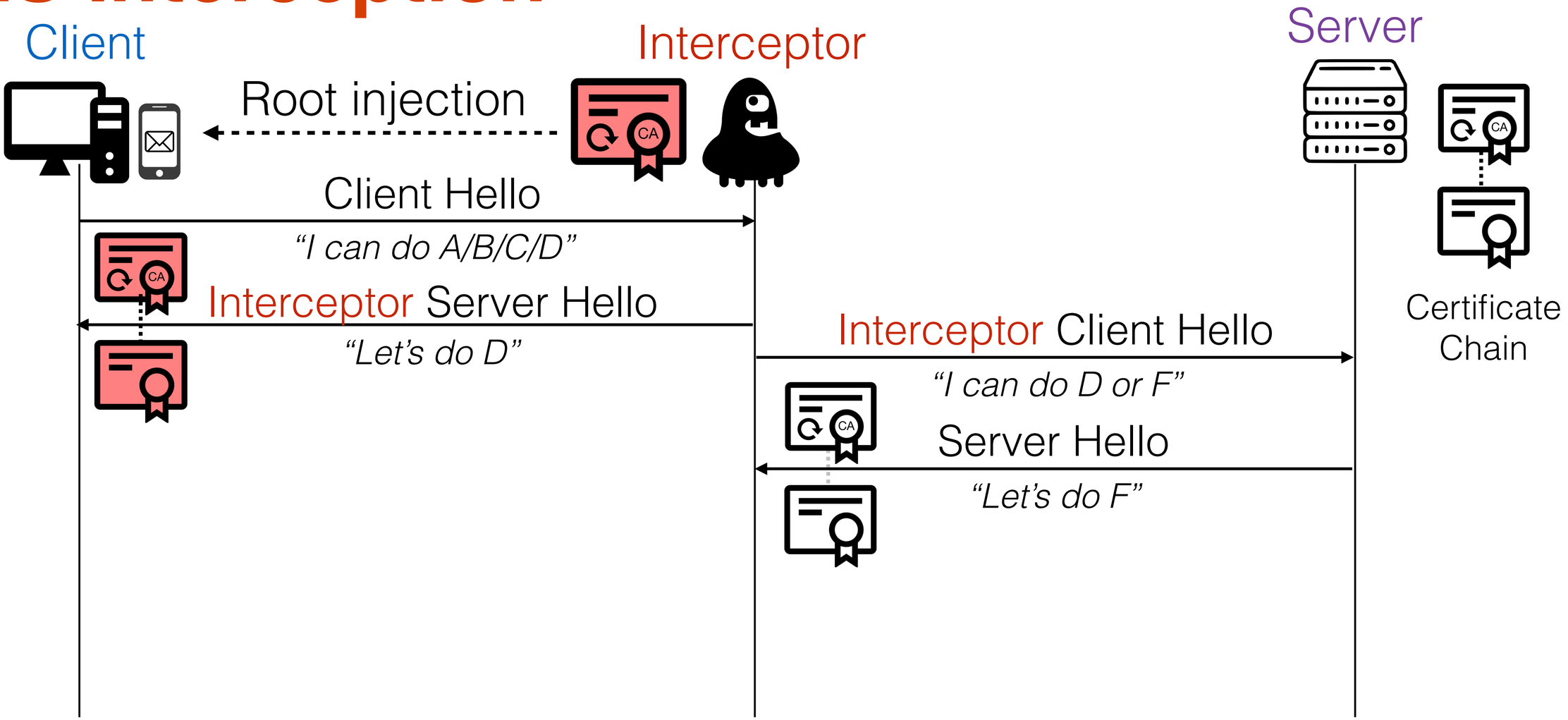
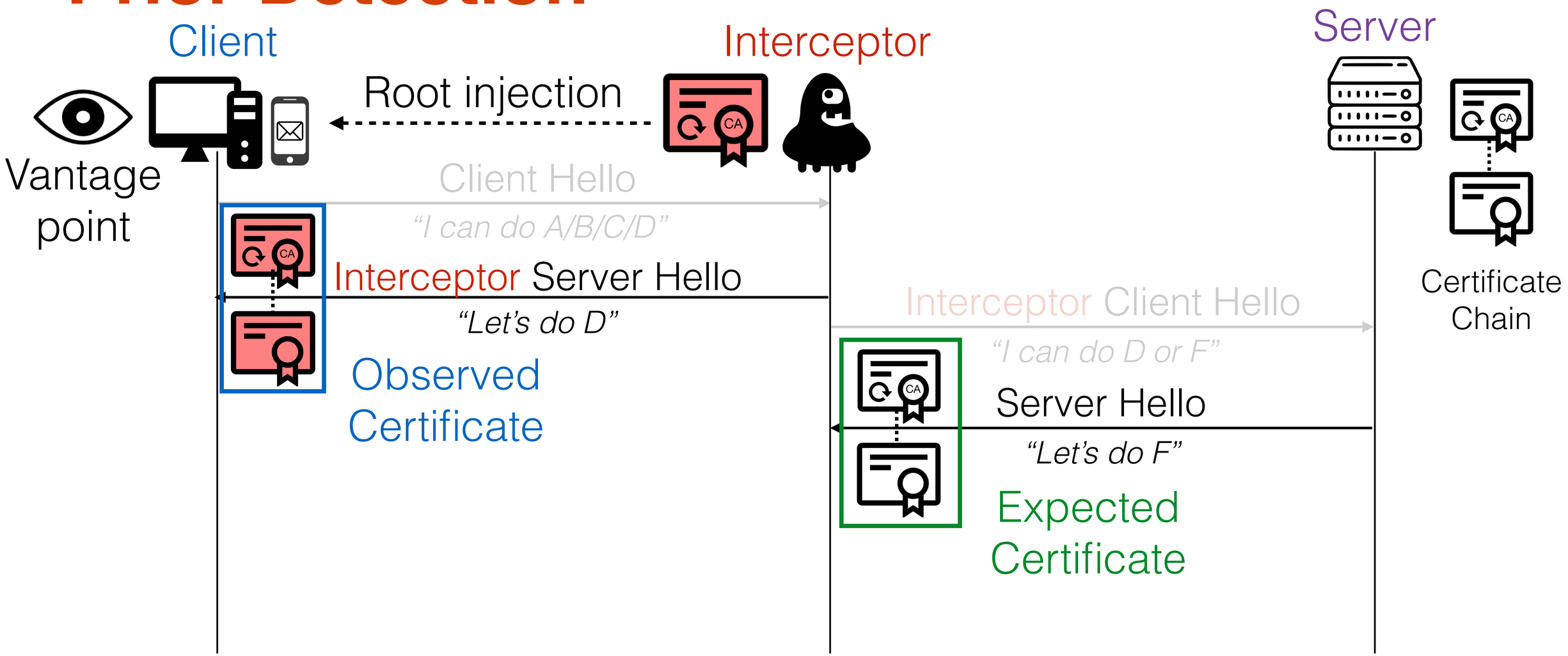


Prior Detection



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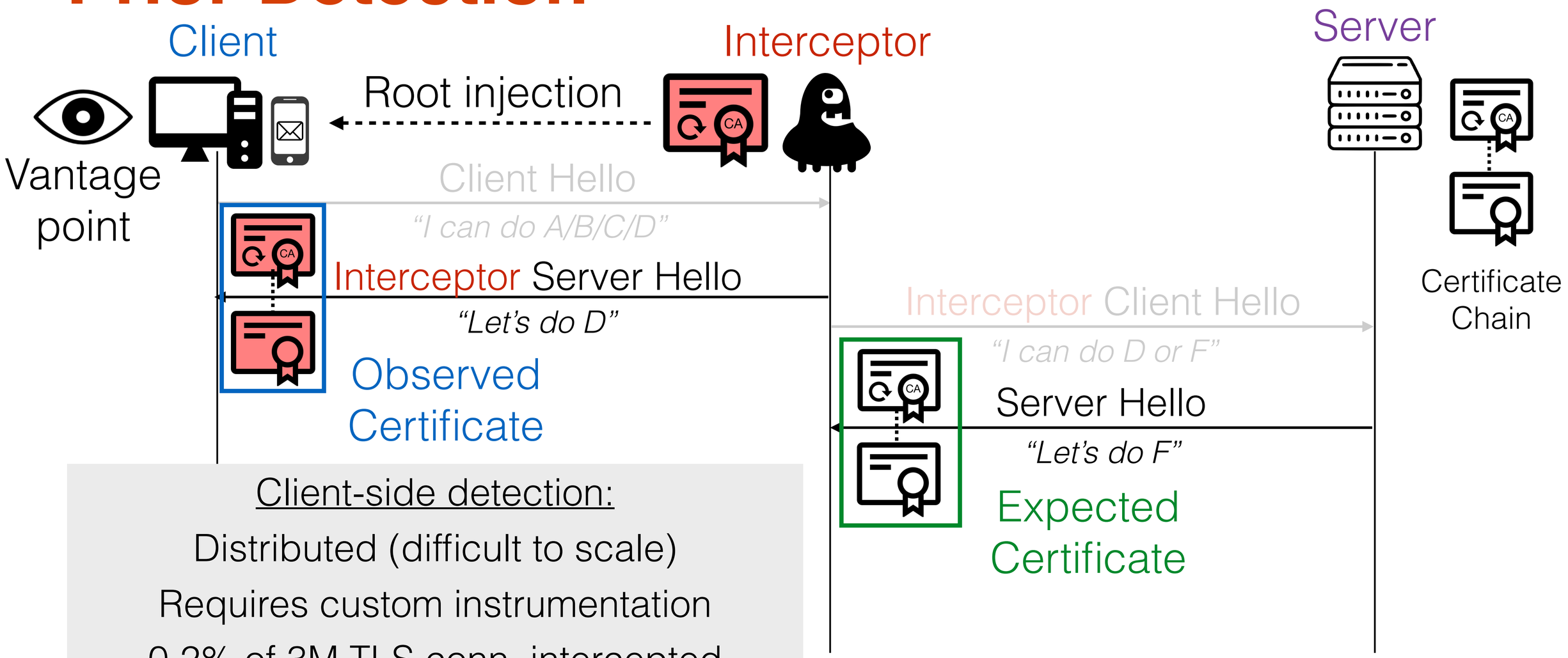


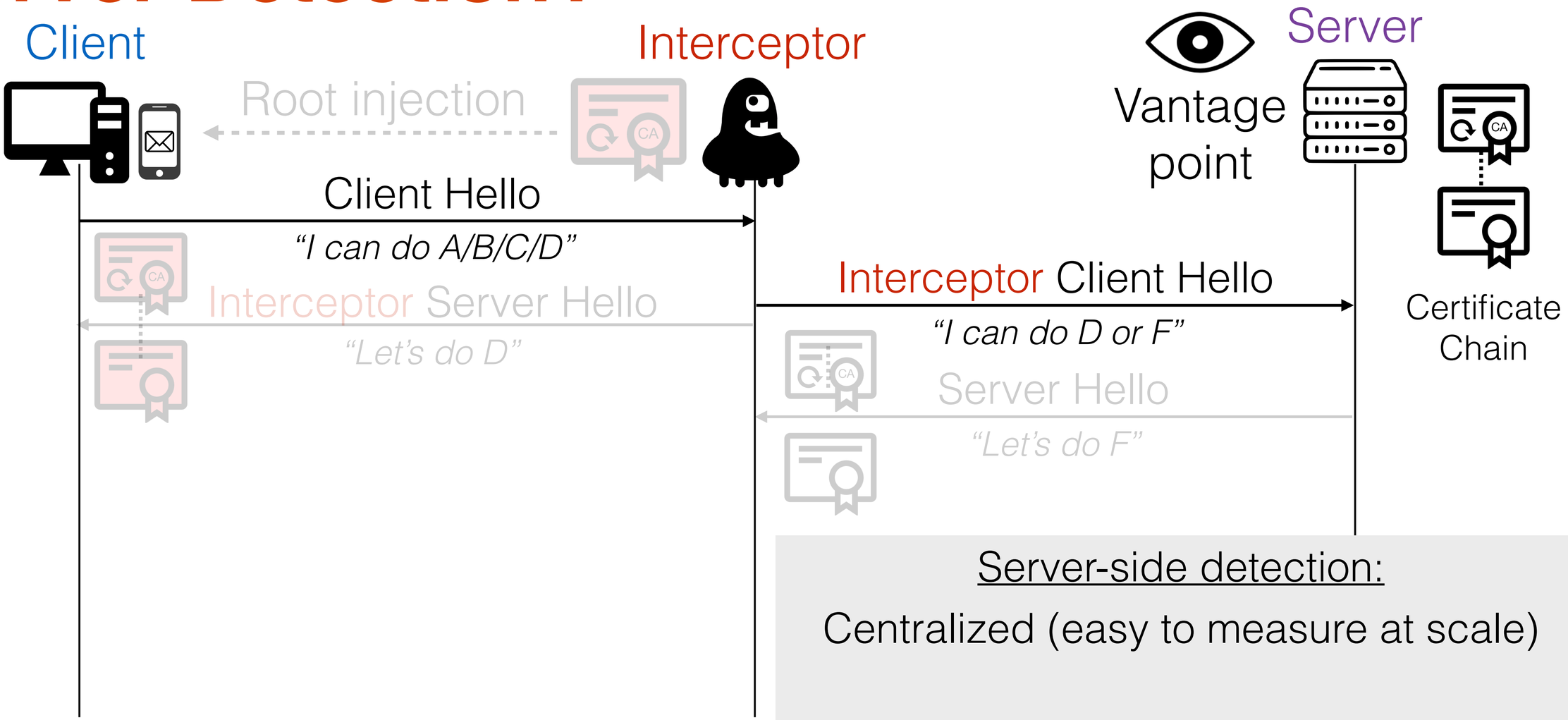
Client-side detection:

Distributed (difficult to scale)

Requires custom instrumentation

0.2% of 3M TLS conn. intercepted

Server Detection?

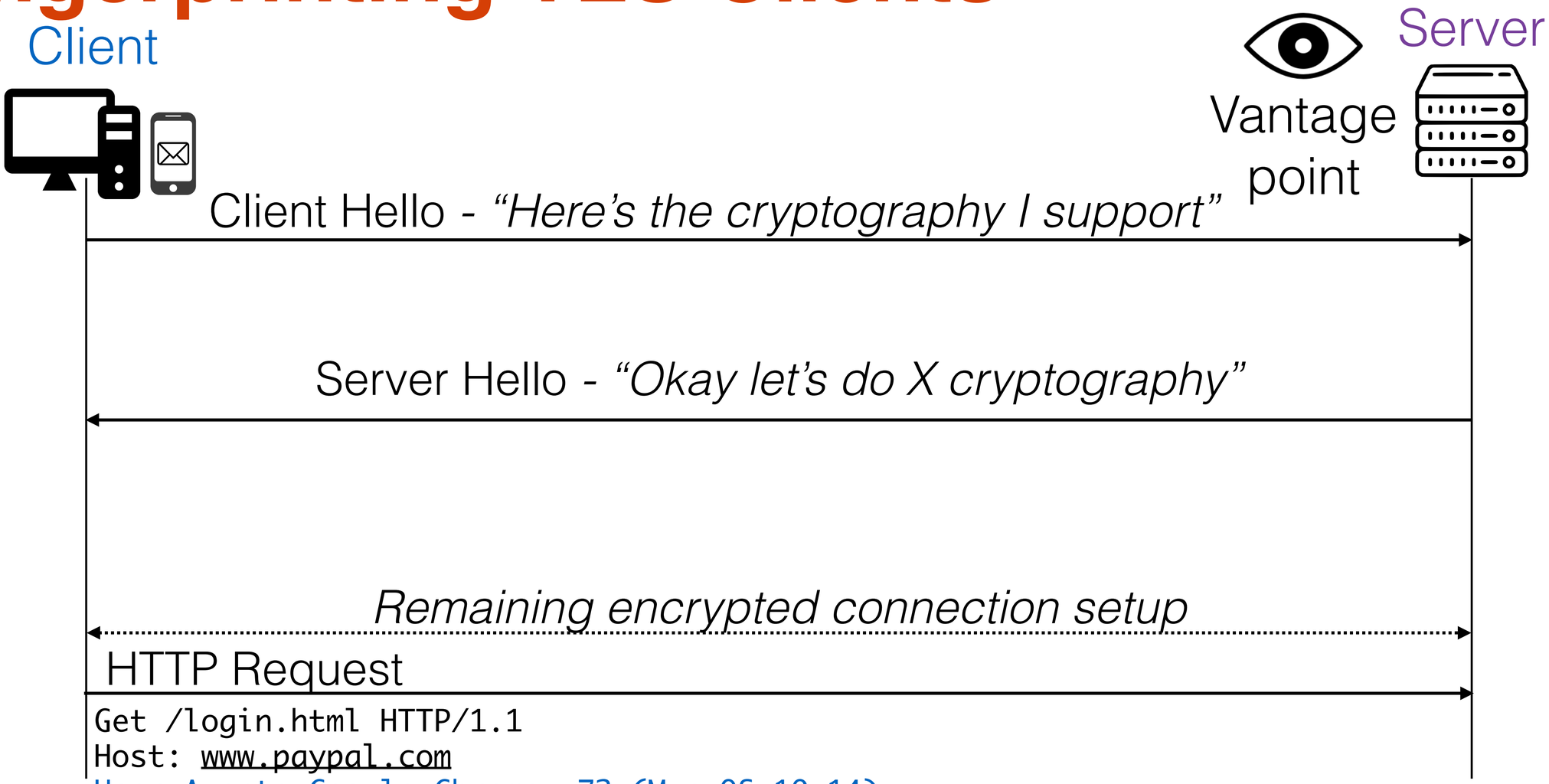


<u>Server-side detection:</u>

Centralized (easy to measure at scale)

How to know what Client Hello to expect?

Fingerprinting TLS Clients



Fingerprinting TLS Clients

Client

Server

Vantage point

Client Hello - *"Here's the cryptography I support"*

```
Version: TLS 1.2 (0x0303)
Cipher Suites
 TLS_ECDHE_ECDSA_WITH_AES_128_GCM_SHA256
 TLS_ECDHE_RSA_WITH_AES_128_GCM_SHA256
Extension: ec_point_formats
 EC point format: uncompressed
Extension: elliptic_curves
 secp256r1 (0x0017)
 secp256r1 (0x0018)
Extension: Application Layer Protocol Negotiation
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Remaining encrypted connection setup

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User-Agent: Google Chrome v72 (Mac OS 10.14)
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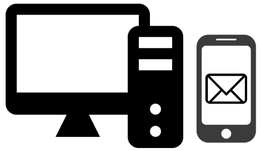

Client Hello

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Version: TLS 1.2 (0x0303)
Cipher Suites
 TLS_ECDHE_ECDSA_WITH_AES_128_GCM_SHA256
 TLS_ECDHE_RSA_WITH_AES_128_GCM_SHA256
Extension: ec_point_formats
 EC point format: uncompressed
Extension: elliptic_curves
 secp256r1 (0x0017)
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Extension: Application Layer Protocol Negotiation
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HTTP Request

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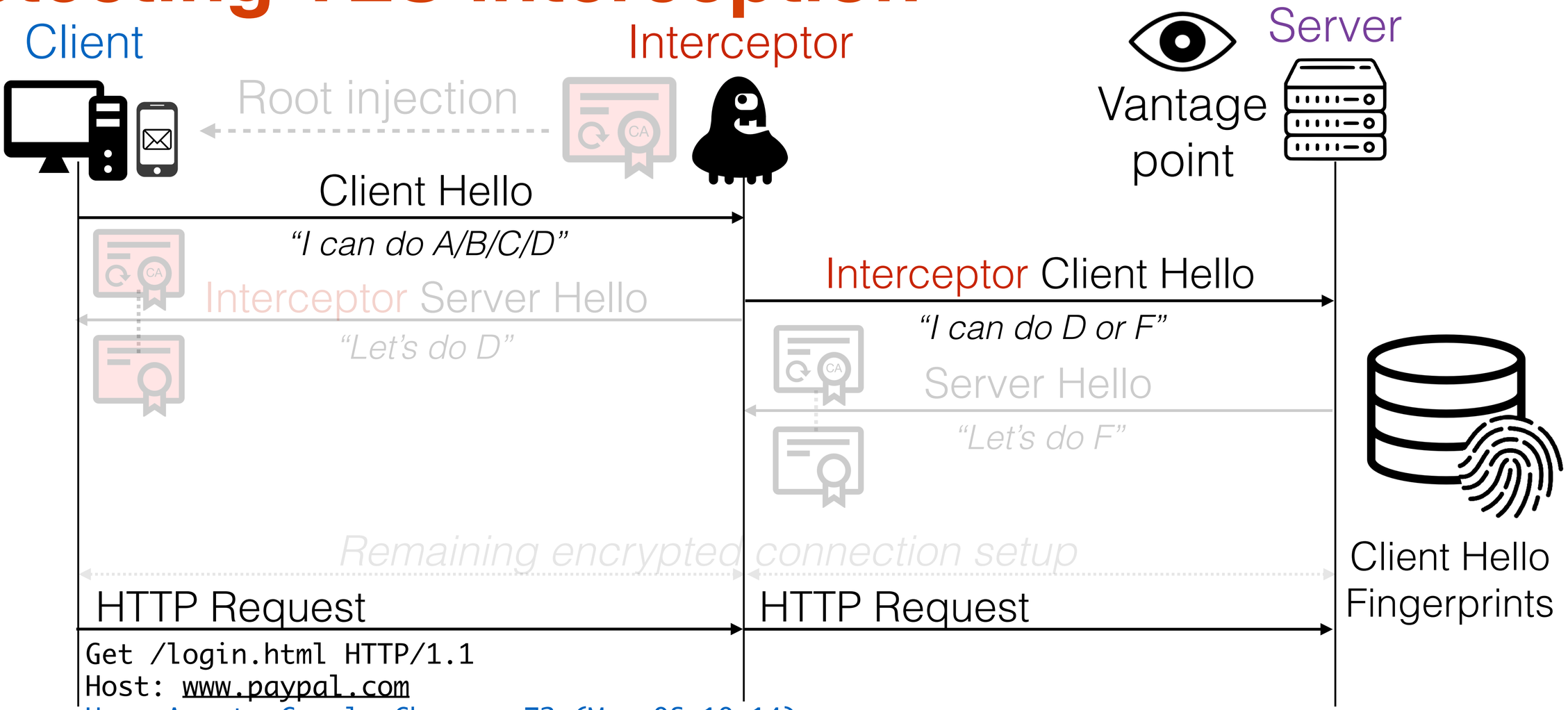
Get /login.html HTTP/1.1
Host: www.paypal.com
User-Agent: Google Chrome v72 (Mac OS 10.14)
```

Catalog of Client Hello fingerprints for popular TLS client User-Agents (e.g., web browsers)

Detecting TLS interception

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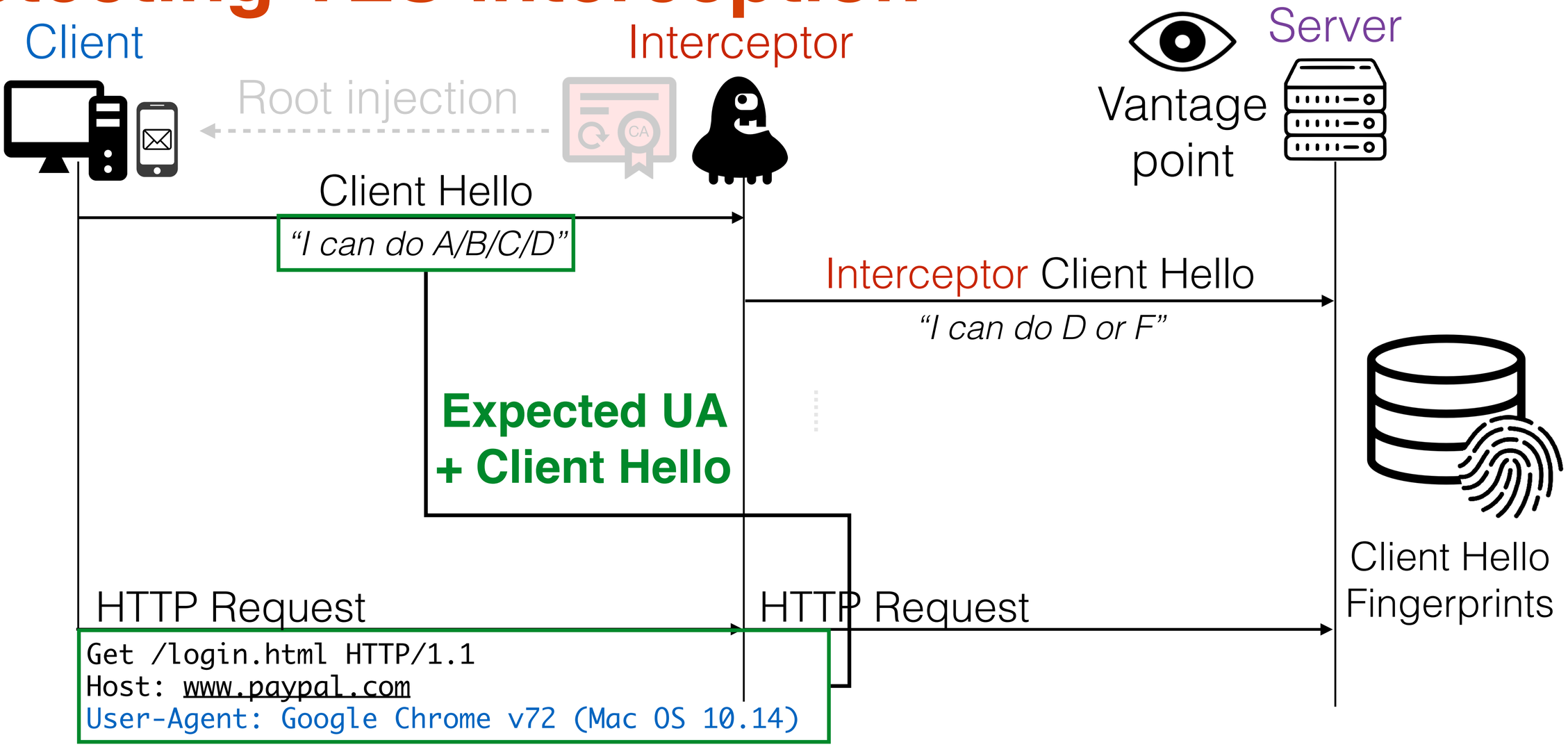

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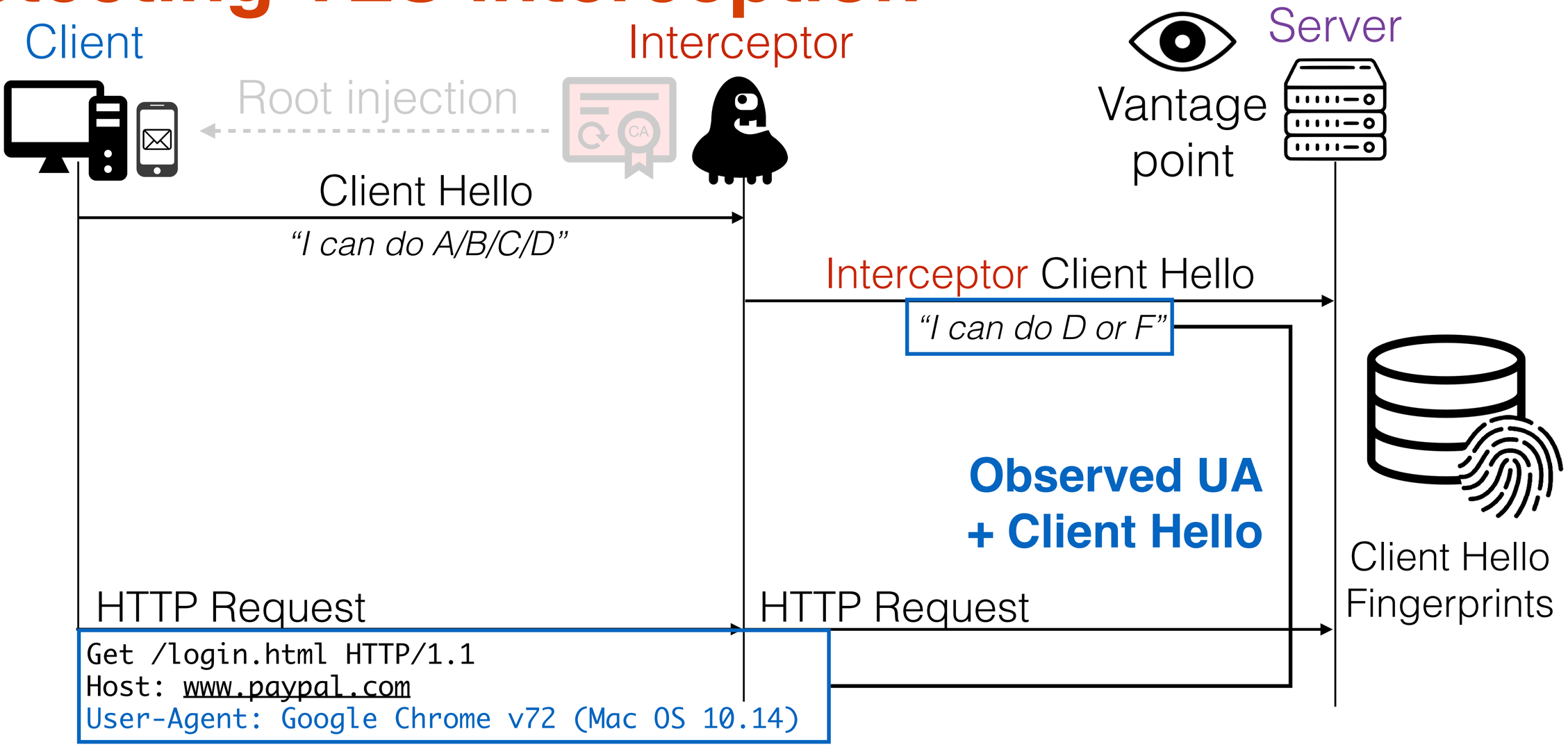


TLS Interception Rates

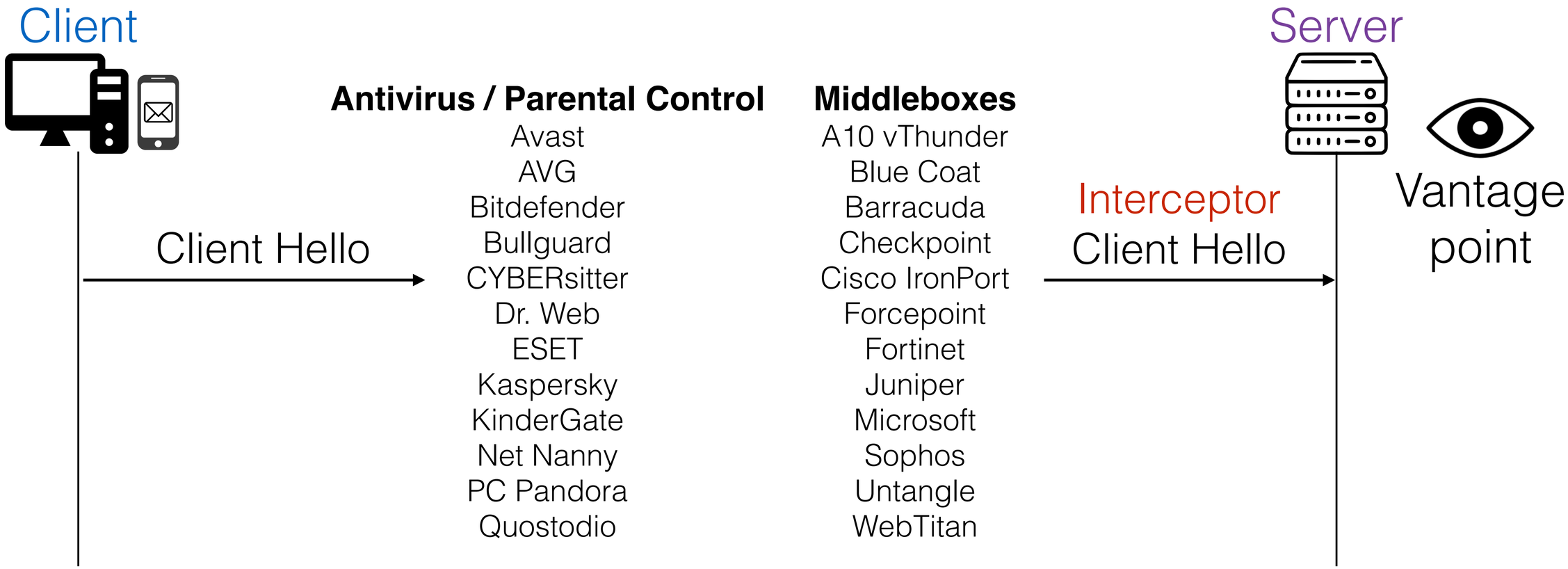
Dataset	Description
Firefox	Daily update check
Amazon	Invisible pixel load via JavaScript
Cloudflare	5% sample of all CDN traffic

2500x prior research

TLS Interception Rates

Dataset	Description	% of TLS conn. intercepted
Firefox	Daily update check	4.0%
Amazon	Invisible pixel load via JavaScript	6.2%
Cloudflare	5% sample of all CDN traffic	10.9%
	8 billion total TLS connections 2500x prior research	**20-50x more interception**

Attributing Interception



Top TLS Interceptors

Dataset	Fingerprint	% Total Interception
Firefox	*Unknown A*	17.1%
	Avast Antivirus	10.8%
	Unknown B	9.4%
	Blue Coat Middlebox	9.1%
	Unknown C	8.3%
Amazon	Avast Antivirus	9.1%
	AVG Antivirus	7.0%
	Unknown D	6.5%
	Kaspersky Antivirus	5.0%
	BitDefender Antivirus	3.1%
Cloudflare	Bouncy Castle (Android 5)	26.3%
	Bouncy Castle (Android 4)	21.6%
	Unknown E	5.0%
	ESET Antivirus	2.8%
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Top TLS Interceptors

Dataset	Fingerprint	% Total Interception
Firefox	*Unknown A*	17.1%
	Avast Antivirus	10.8%
	Unknown B	9.4%
	Blue Coat Middlebox	9.1%
	Unknown C	8.3%
Amazon	Avast Antivirus	9.1%
	AVG Antivirus	7.0%
	Unknown D	6.5%
	Kaspersky Antivirus	5.0%
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Cloudflare	Bouncy Castle (Android 5)	26.3%
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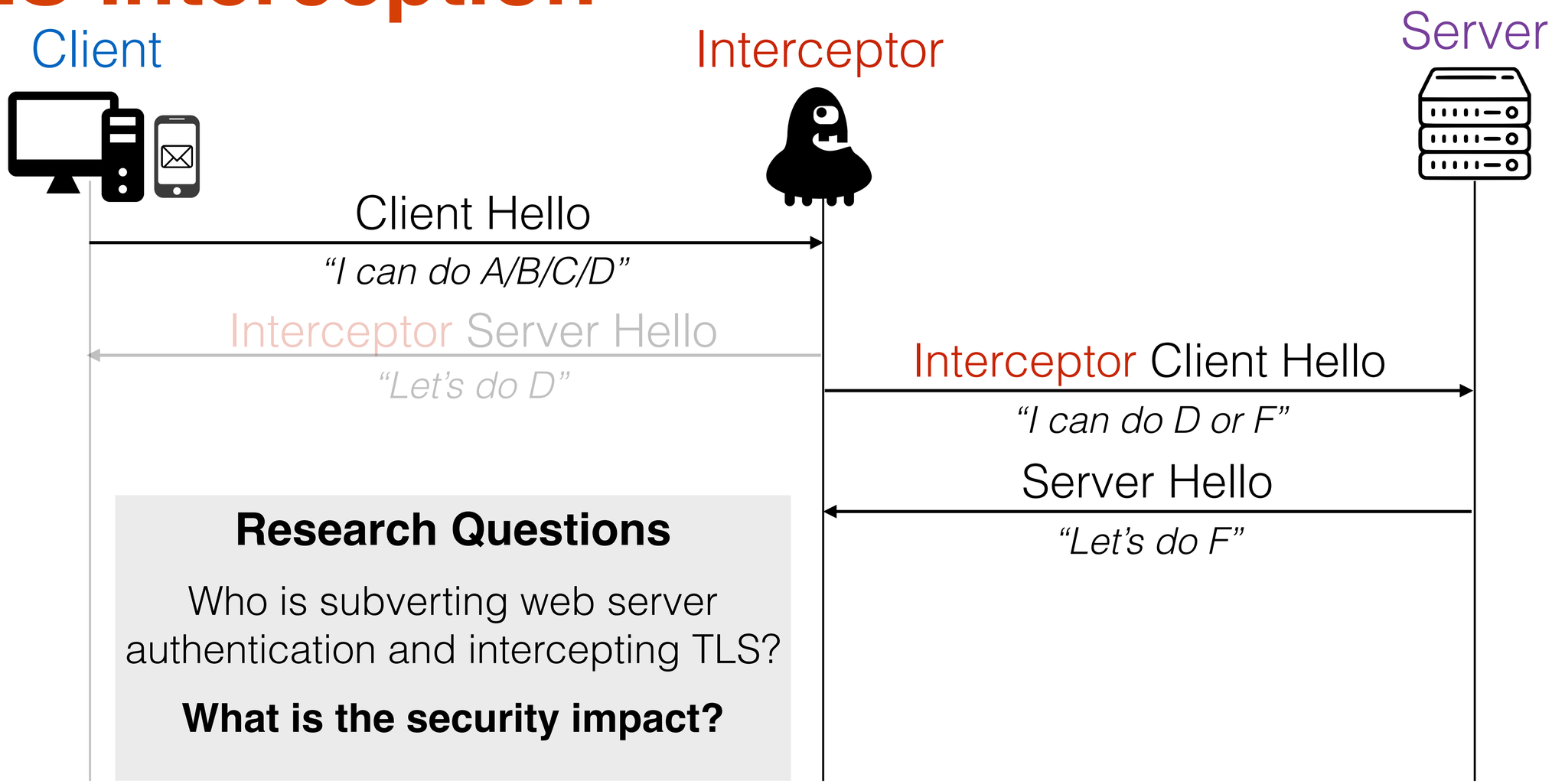
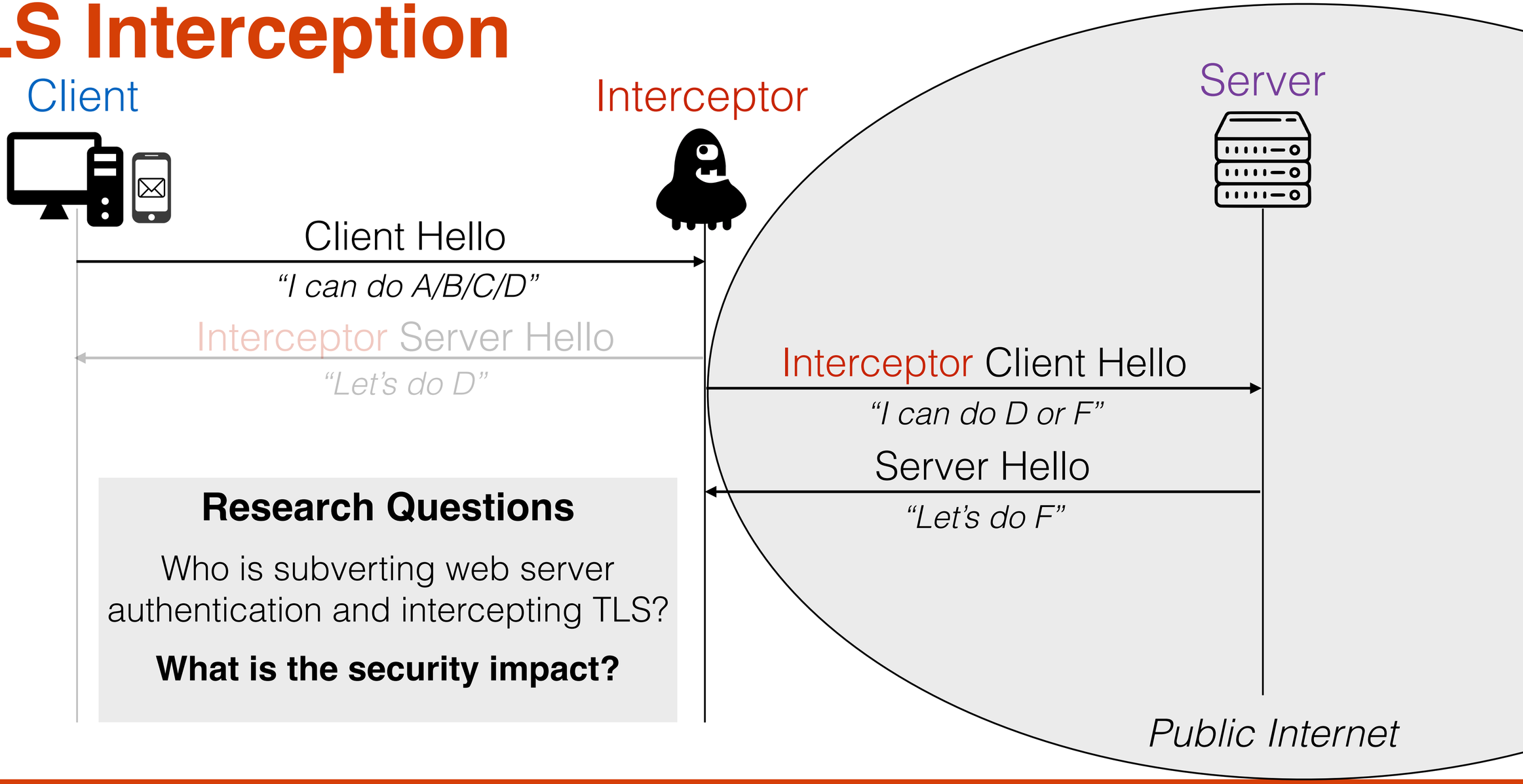


Research Questions

Who is subverting web server authentication and intercepting TLS?

What is the security impact?

TLS Interception



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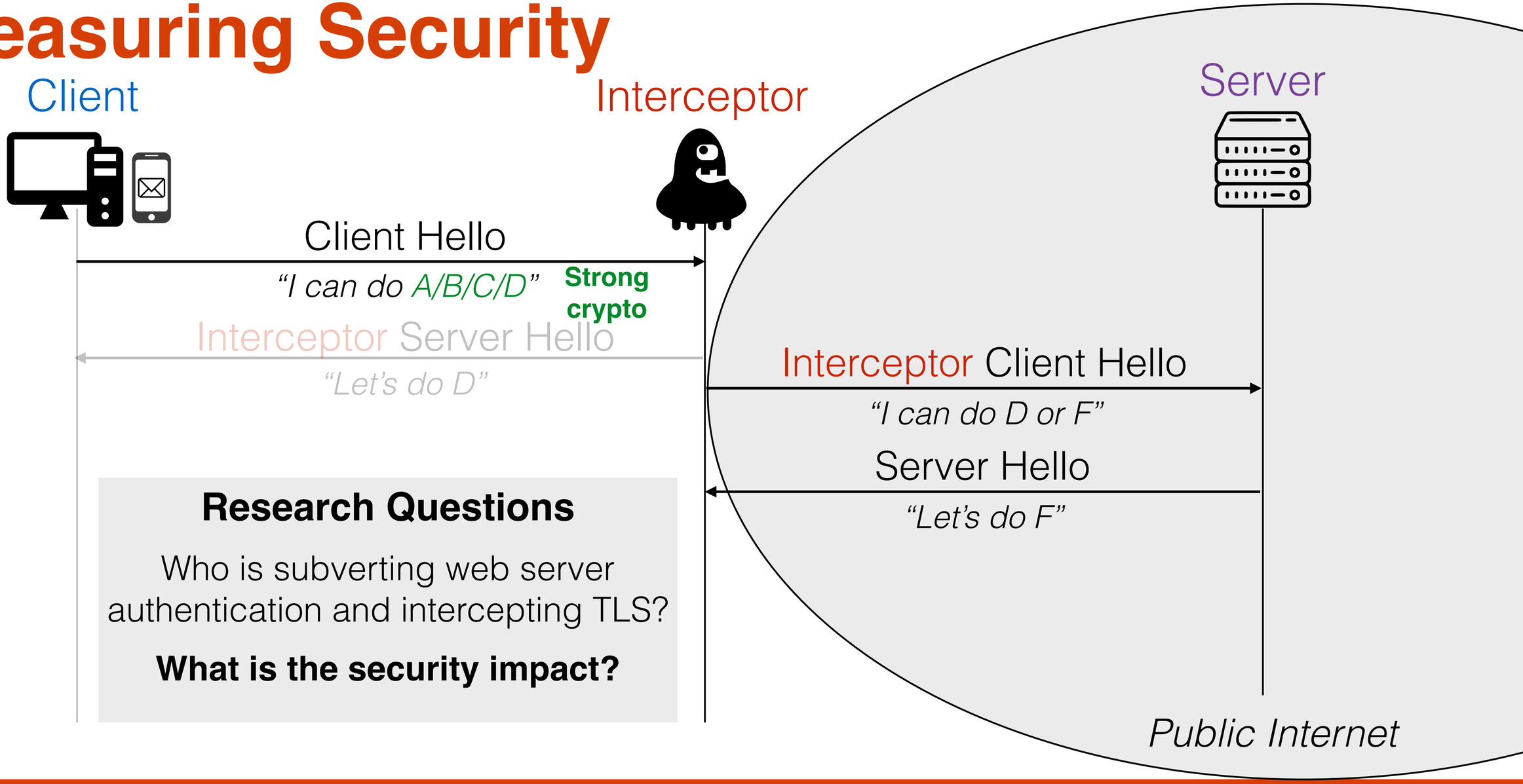
Measuring Security



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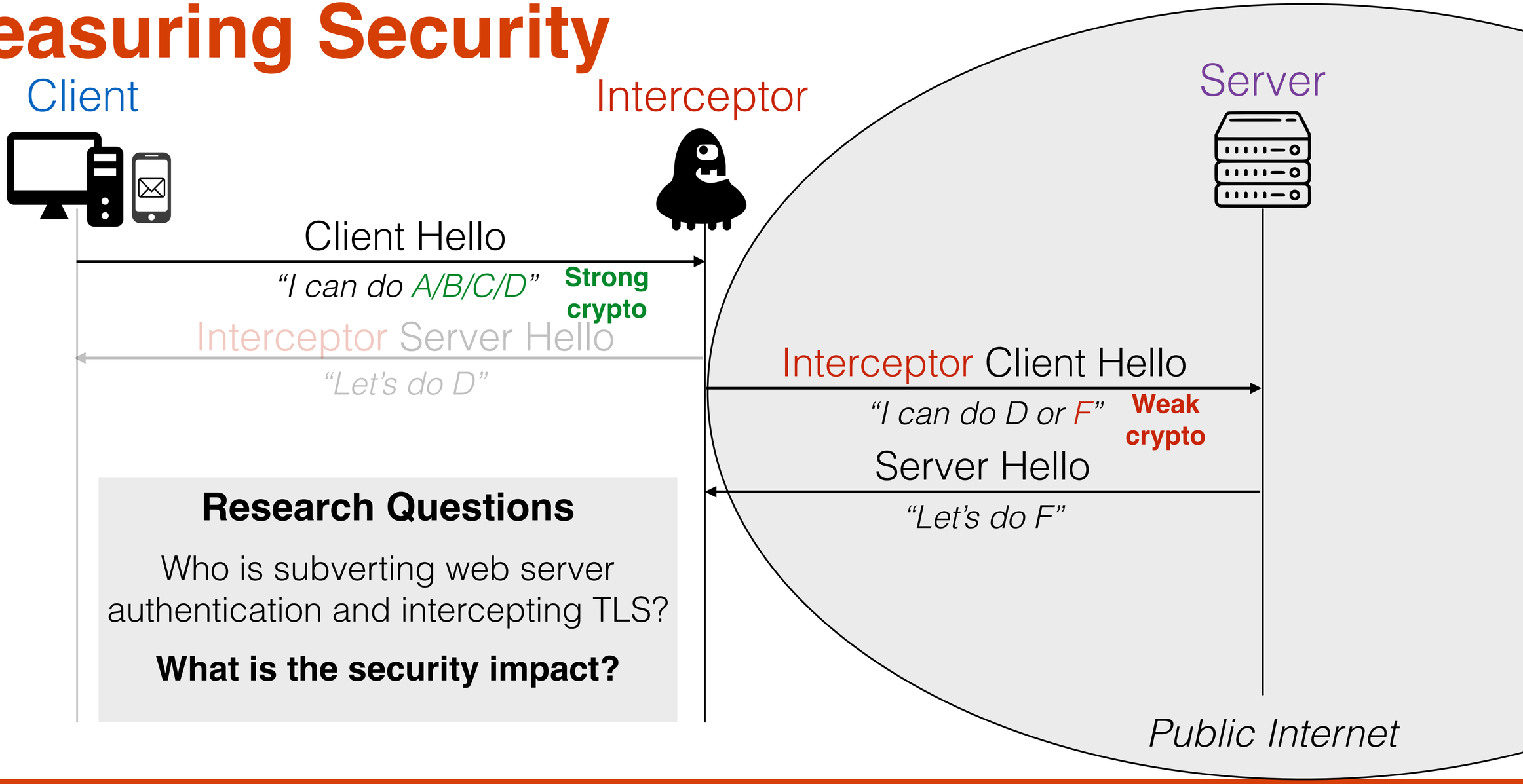

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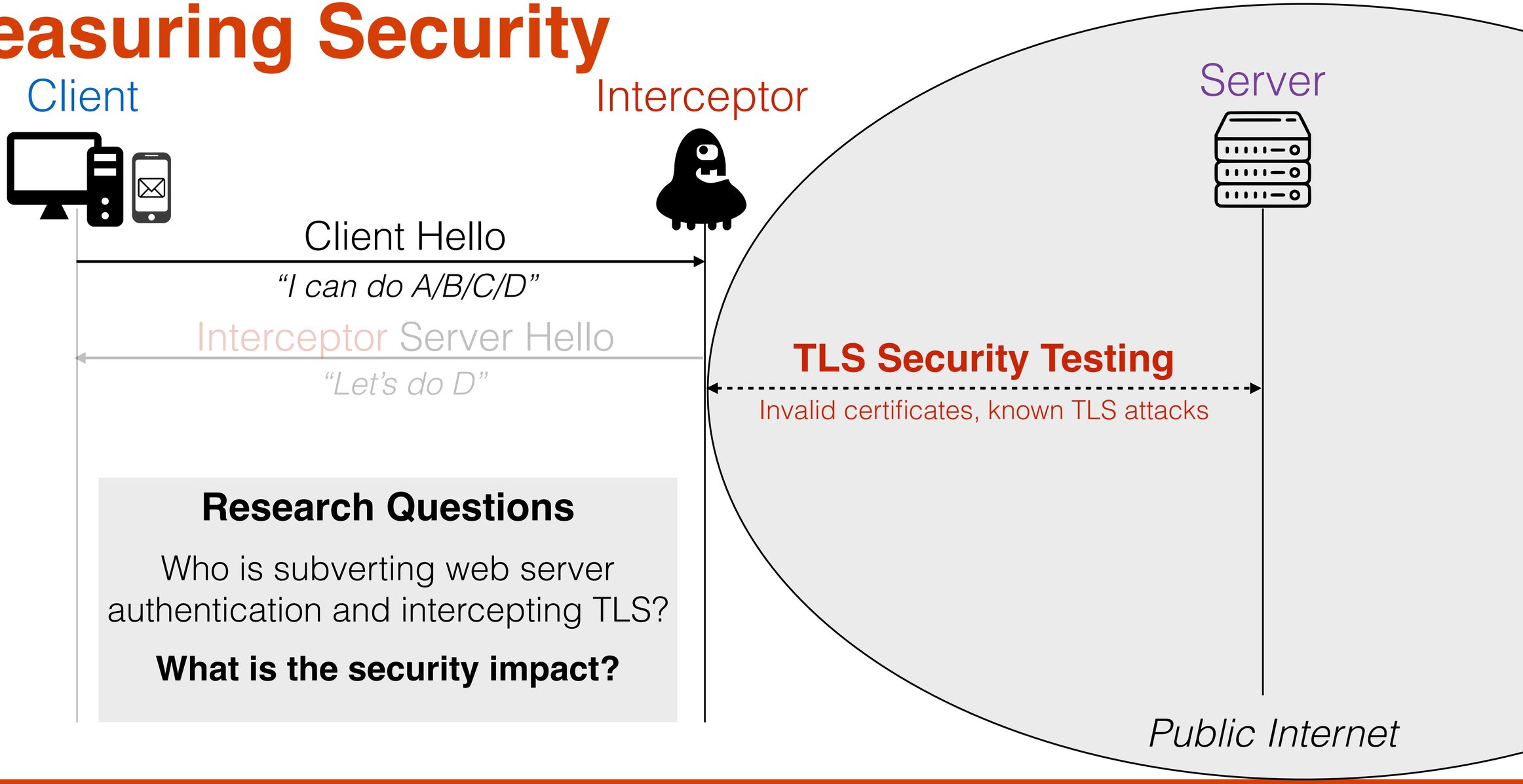

Research Questions

Who is subverting web server authentication and intercepting TLS?

What is the security impact?

Results

Dataset	Original Security	Intercepted Security			
		A	B	C	F
Firefox	A	34.3%	16.8%	12.2%	36.8%
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	B	2.7%	10.2%	1.2%	8.3%
	C	0.6%	0.4%	1.0%	0.3%
	F	0.0%	0.2%	0.1%	1.0%
Cloudflare	A	7.4%	1.1%	29.7%	10.0%
	B	0.0%	0.0%	0.0%	0.0%
	C	9.4%	3.3%	22.0%	4.5%
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Rubric

A = Optimal

B = Not vulnerable

C = Known attack

F = Severely broken

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	F	0.0%	0.2%	0.1%	1.0%
Amazon (middlebox)	A	13.5%	3.0%	0.8%	18.0%
	B	0.7%	23.3%	0.6%	37.8%
	C	0.1%	0.1%	0.0%	2.2%
	F	0.0%	0.0%	0.0%	0.0%

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Interceptor Transparency

US Computer Emergency Readiness Team (US-CERT) issued alert [1]

6 vendors patched vulnerabilities

CYBERSECURITY & INFRASTRUCTURE SECURITY AGENCY

Alert (TA17-075A)

HTTPS Interception Weakens TLS Security

Original release date: March 16, 2017

Print Tweet Send Share

Systems Affected

All systems behind a hypertext transfer protocol secure (HTTPS) interception product are potentially affected.

[1] https://www.cisa.gov/uscert/ncas/alerts/TA17-075A

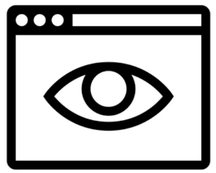
Interceptor Transparency

US Computer Emergency Readiness Team (US-CERT) issued alert [1]

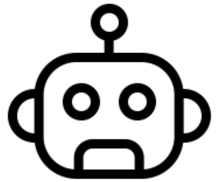
6 vendors patched vulnerabilities

Prompted Cloudflare to deploy continuous, automated monitoring [2]

ClientHello fingerprints popularized by Salesforce as JA3; used to detect:



Censorship detection



Bot detection

IoT detection

[1] https://www.cisa.gov/uscert/ncas/alerts/TA17-075A

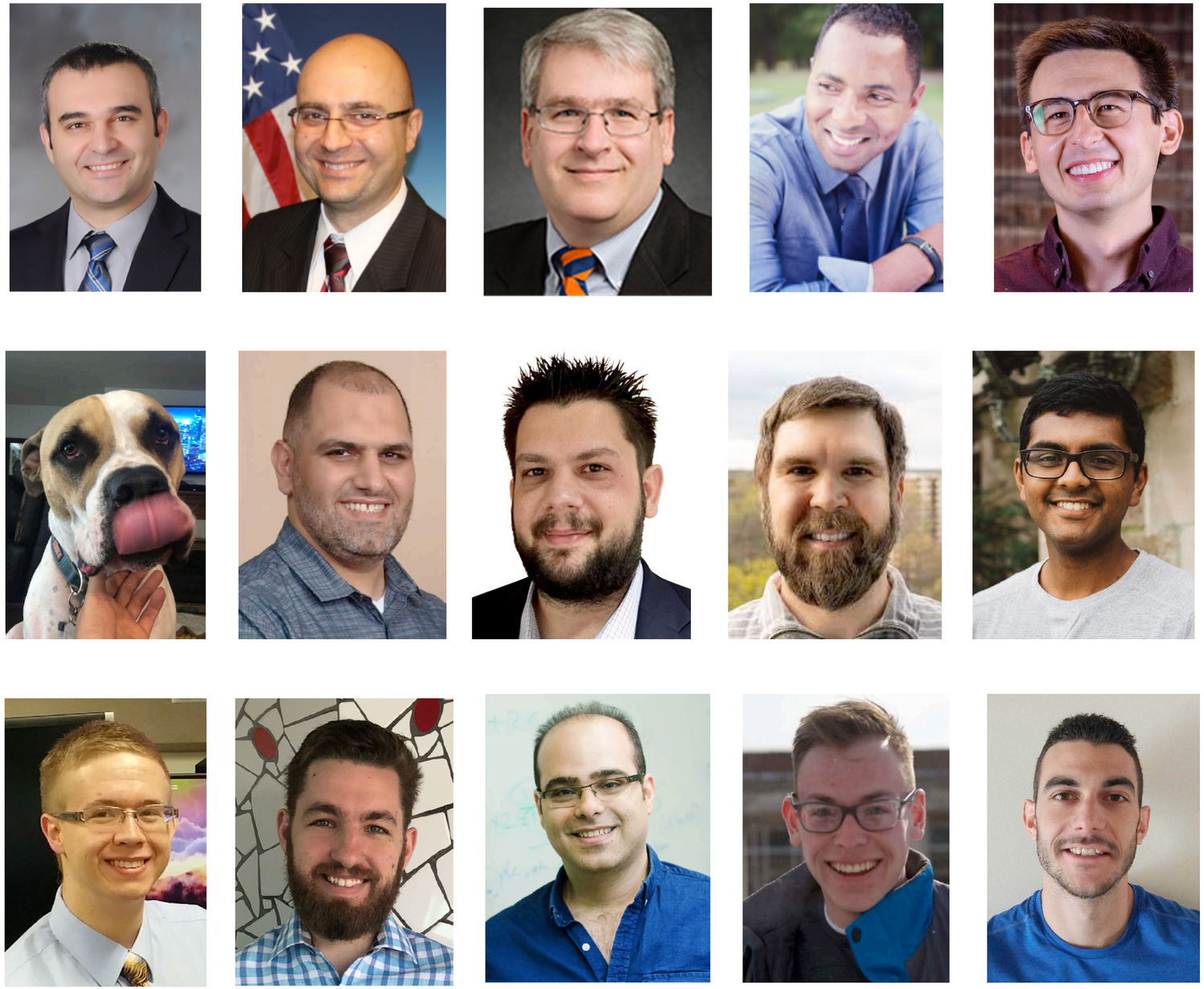
[2] https://malcolm.cloudflare.com/

Collaborators

Georgia Tech

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Stanford University



Peeking into the Web PKI

Uncovering the Trust That Sustains Web Server Authentication

Zane Ma (he/him)
Oregon State University
2024.05.02

Stale TLS Certificates

Investigating Precarious Third-Party Access to Valid TLS Keys

Zane Ma (he/him)
Oregon State University
2023.10.25

Aaron Faulkenberry, Thomas Papastergiou, Zakir Durumeric*, Michael Bailey, Angelos Keromytis, Fabian Monrose, Manos Antonakakis

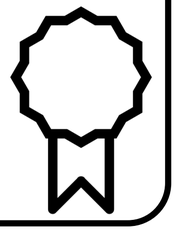
Georgia Institute of Technology *Stanford University

Public-key crypto

Issuer Name: Certificate Authority XYZ

Subject Name: domain.com
Subject Public Key: 0400aefa6edef14a…

Issuer Signature: 19574503953e…



TLS Certificate

Key challenge: linking cryptographic identity (public-key) with semantic identity

TLS certificate = cached attestation

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Validity: 2023-10-20 to 2024-11-19

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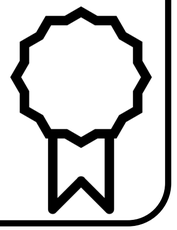

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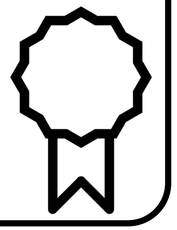

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Subject Public Key: 00c946d6e746f1…

Validity: 2023-10-25 to 2024-11-24

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New TLS Certificate

Stale certificates arise from **certificate invalidation events**: changes to attested information (e.g., subject / issuer info) while certificate is still valid

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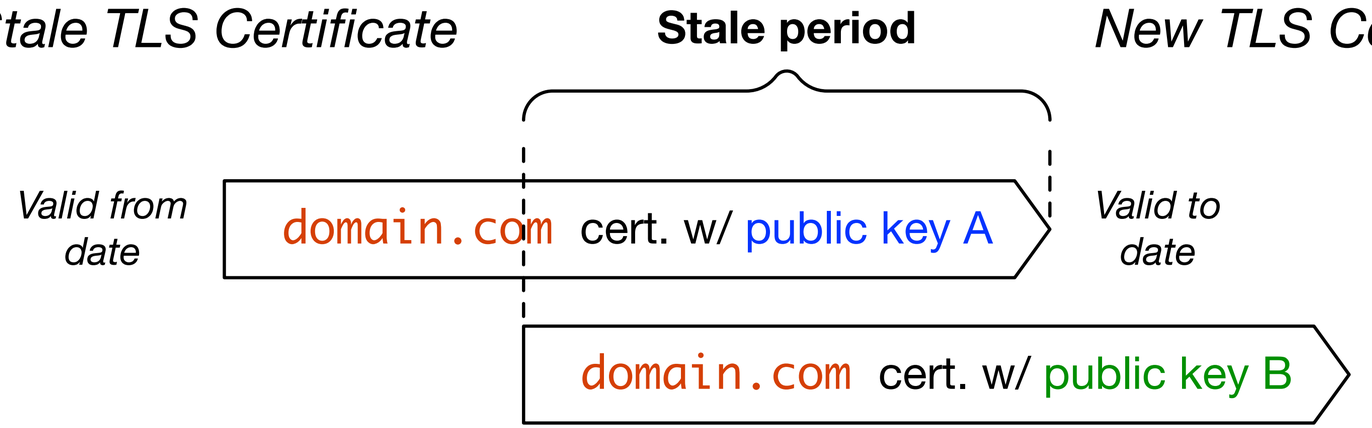

Domain-to-key operational gap

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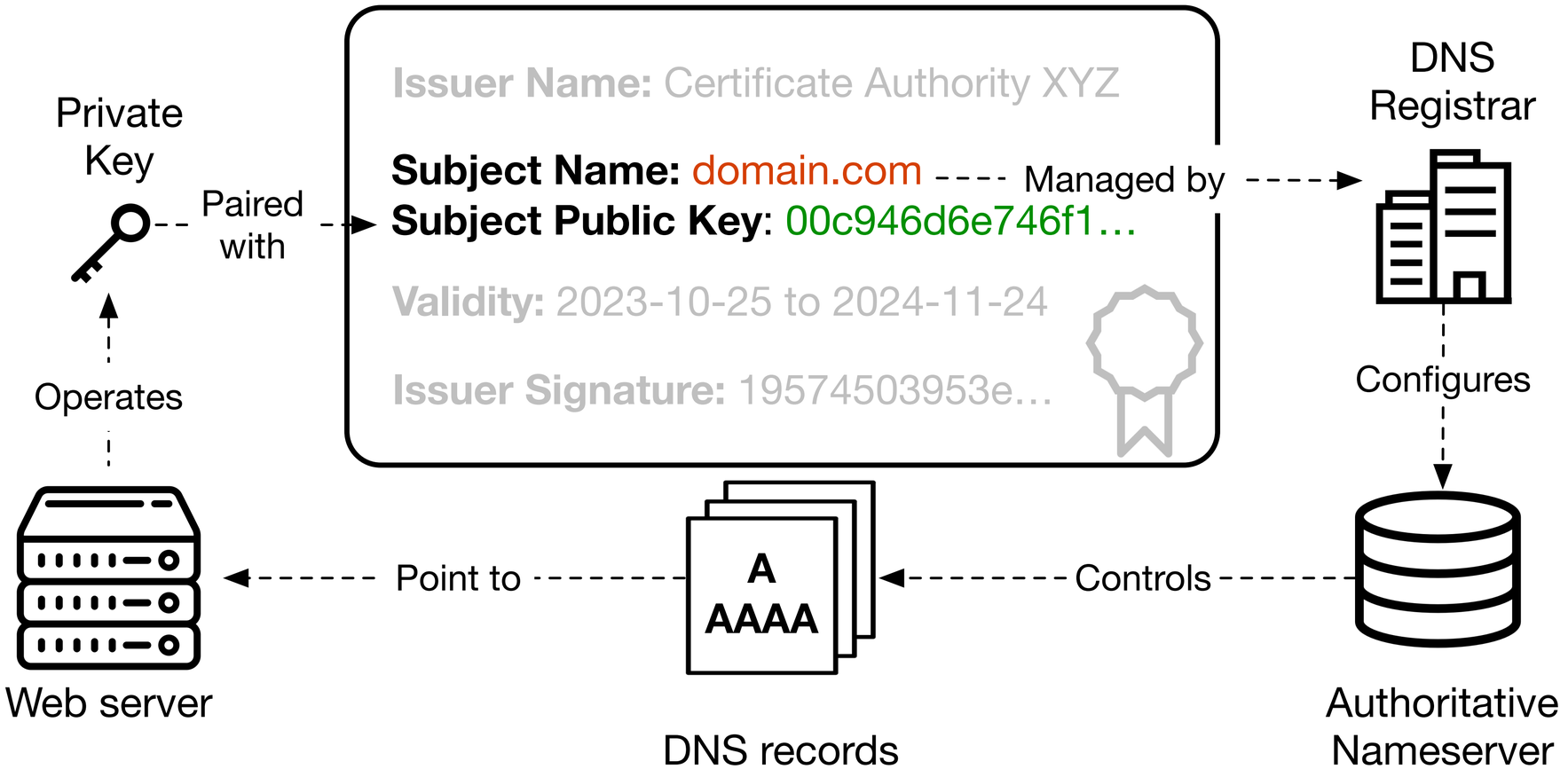
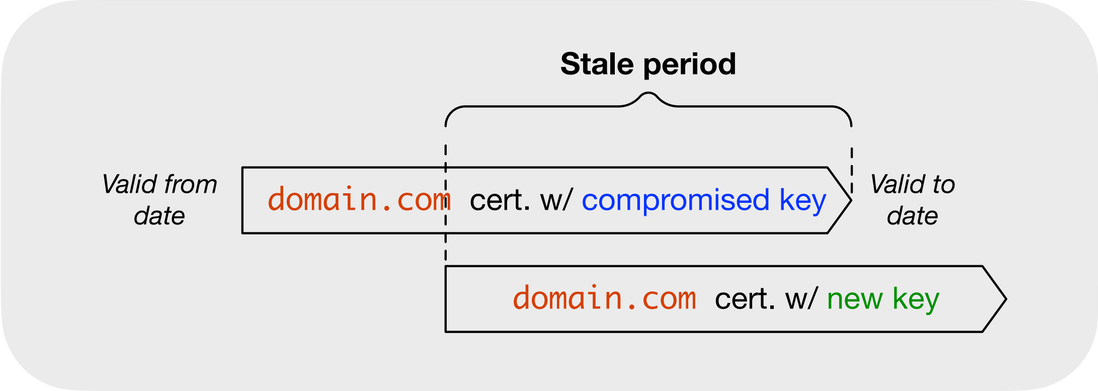


Third-party access to valid TLS keys

Compromised key change



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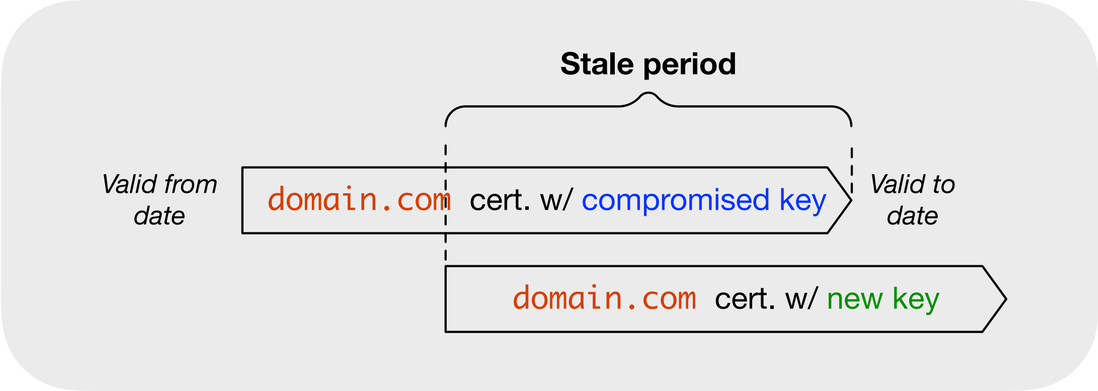

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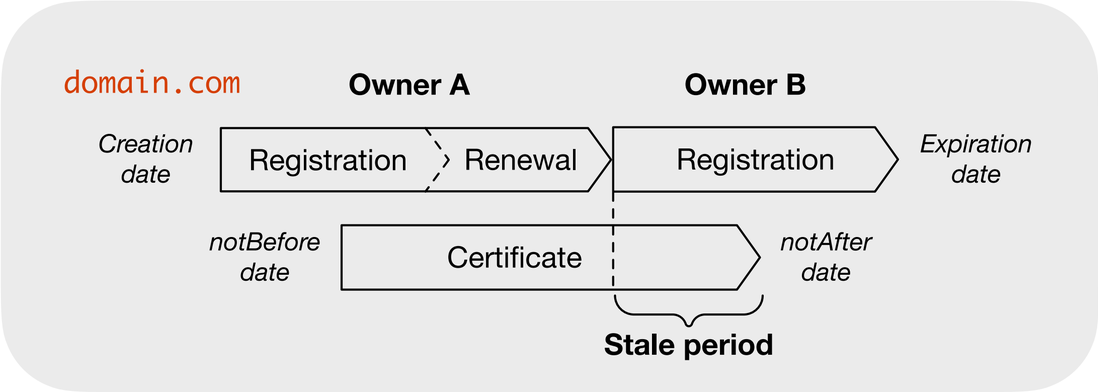

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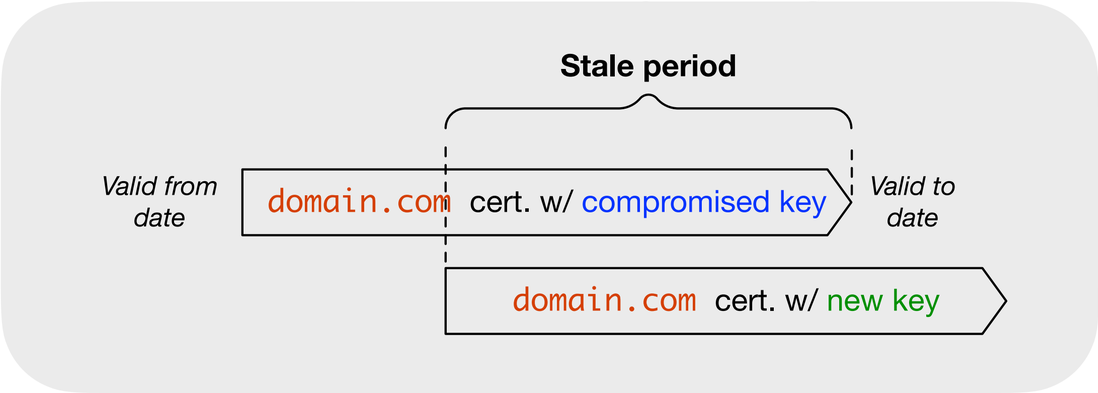

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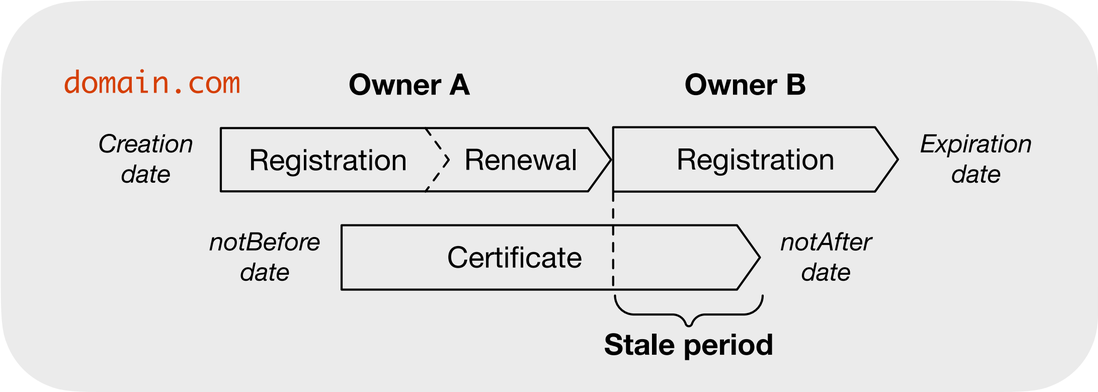
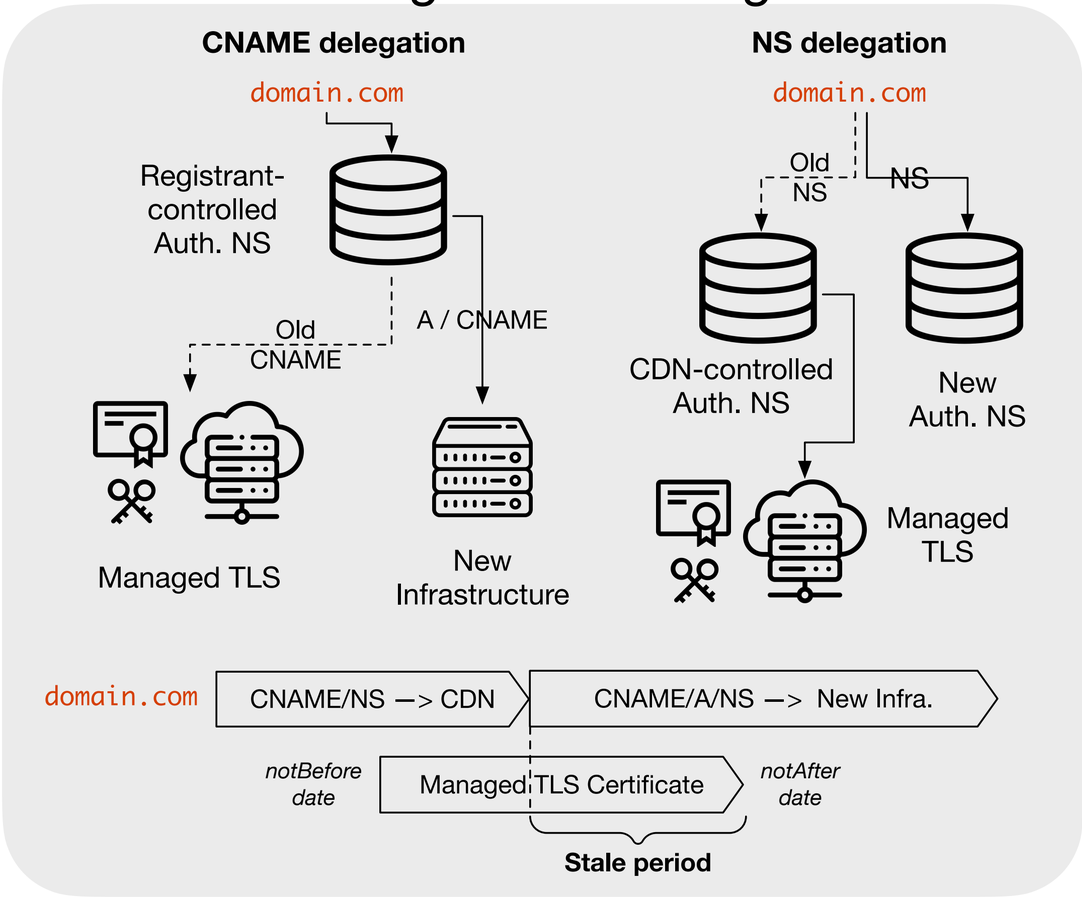


Managed TLS change



Revocation to the rescue?

Web browsers

Chrome has CRLsets primarily
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Firefox OCSP checking fails open
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No revocation checking for most leaf certificate revocation

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Non-browser TLS clients

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LibreSSL

GnuTLS

Mbed TLS

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Revocation is sparse and unreliable

Internet-wide staleness

5B TLS certificates

4B WHOIS records

27B DNS records

31M Revocations

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Third-party Staleness	# certs / day	# FQDNs / day	#e2LD / day
Key compromise	493	787	347

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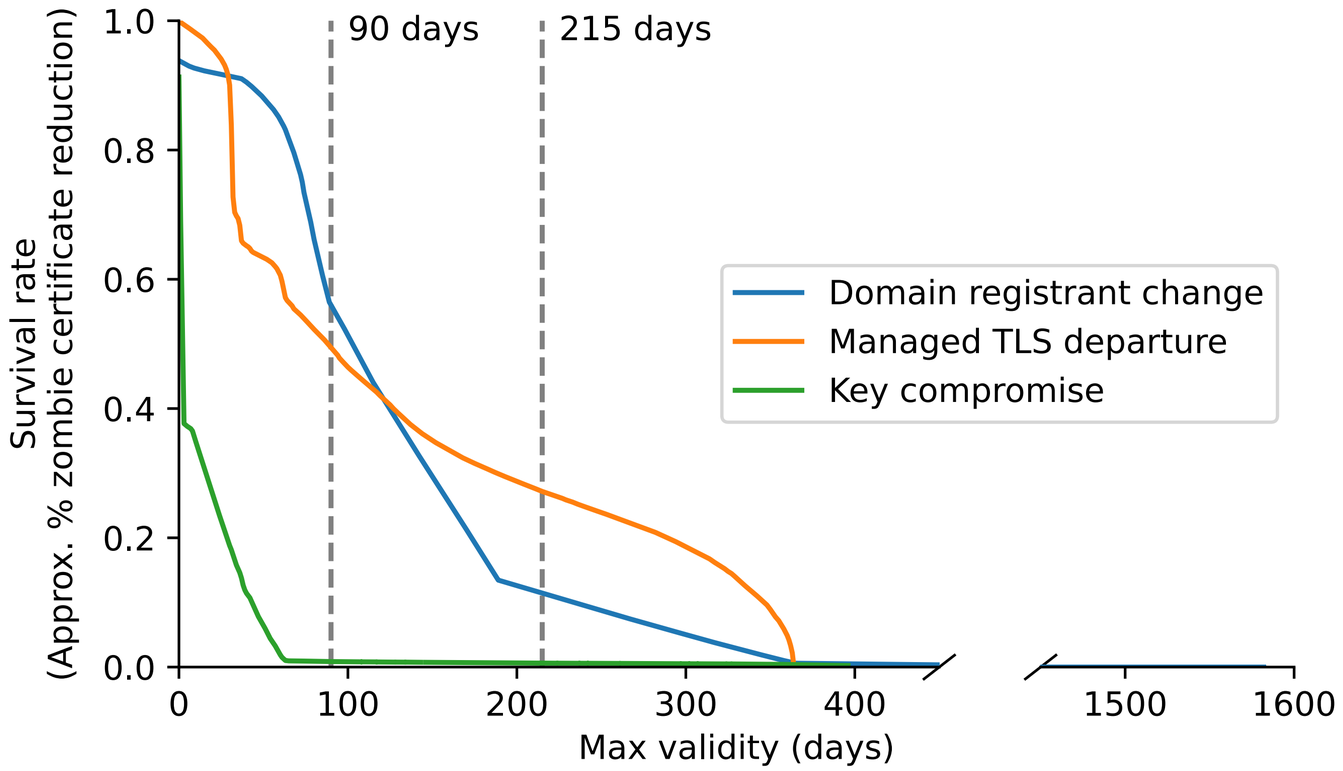
Domain owner change	2,593	2,807	1,214
Cloudflare managed TLS change	9,495	18,833	7,722

What can we do about it?

- Revocation is largely ineffective, and (unsurprisingly) poorly utilized
- Caching problem: reduce certificate lifetimes



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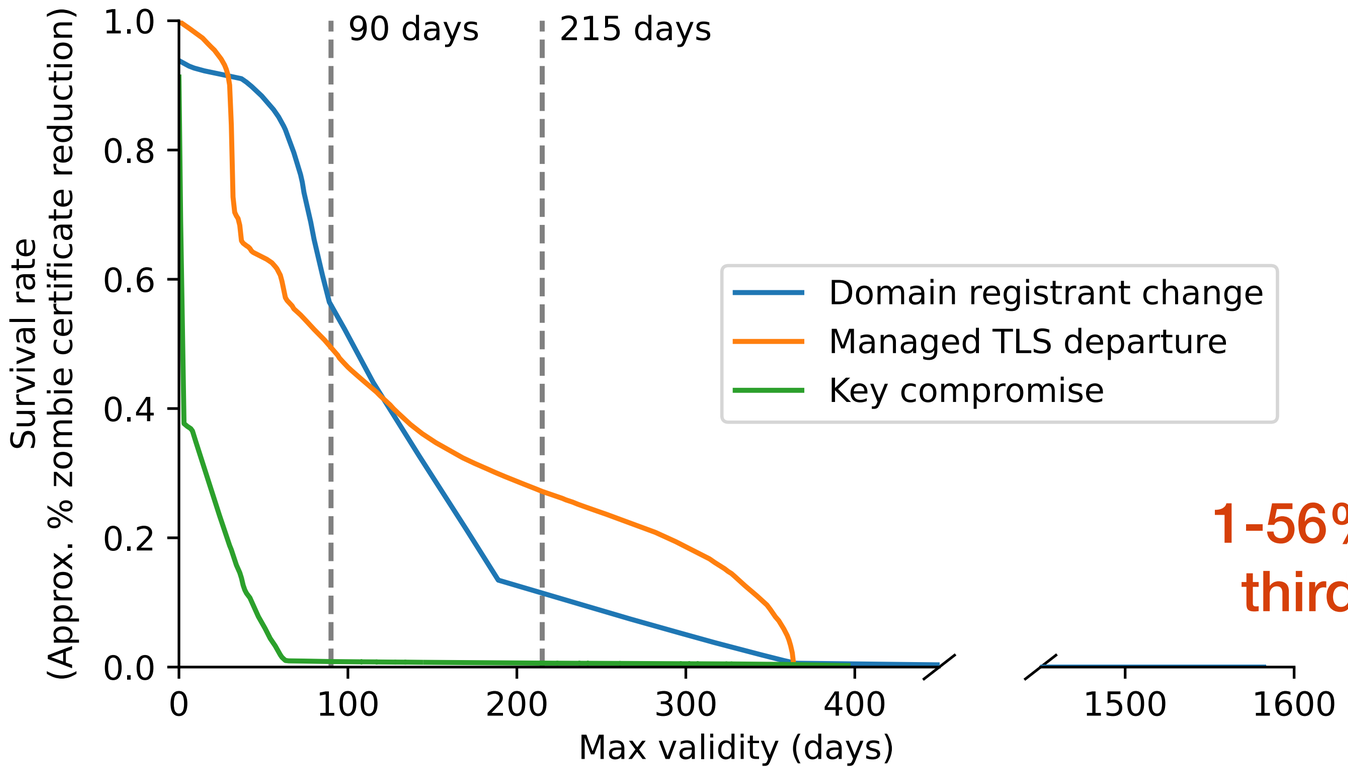
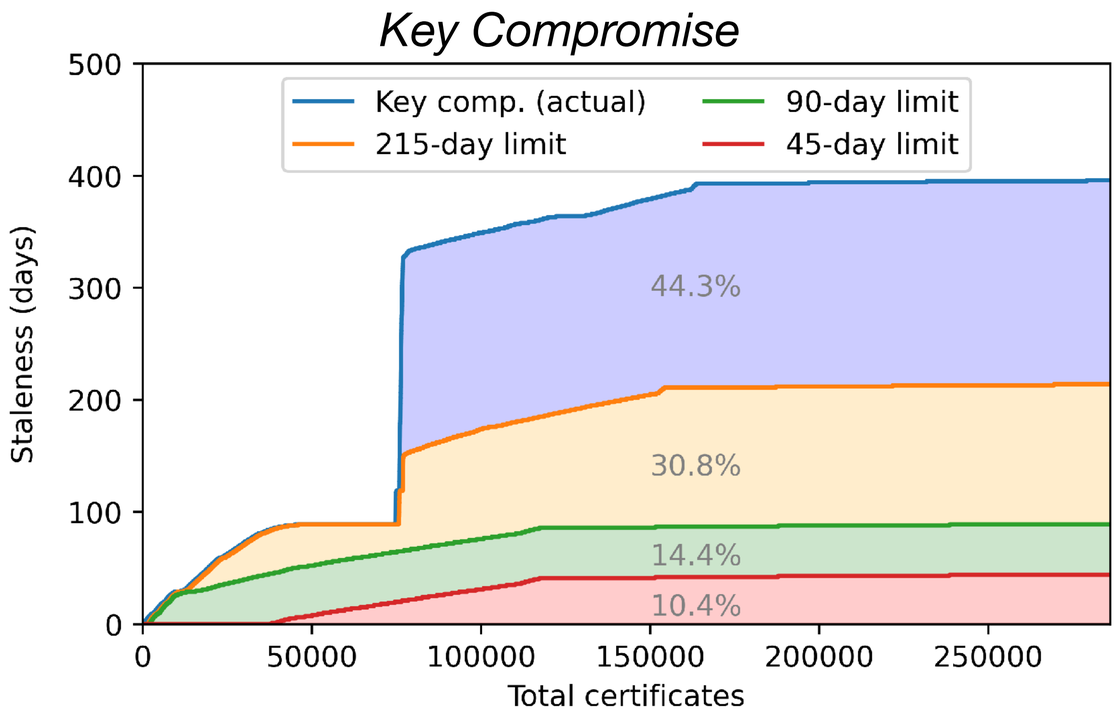
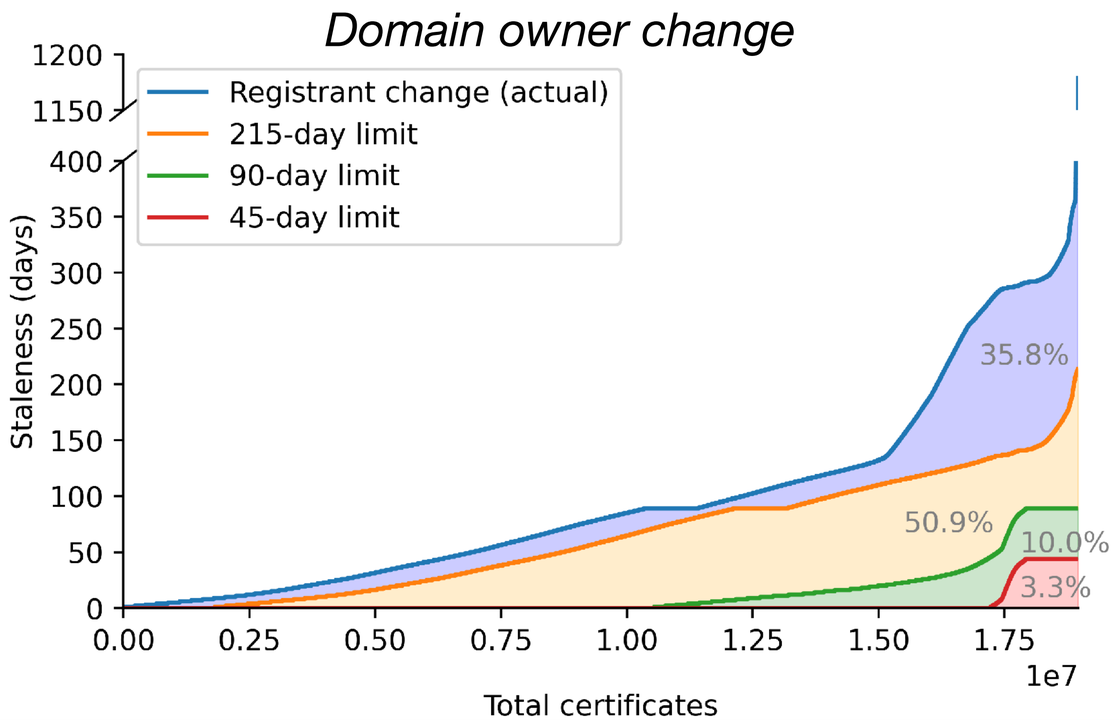


90-day limit = 1-56% reduction in stale third-party certificates

Shortening certificate lifetimes





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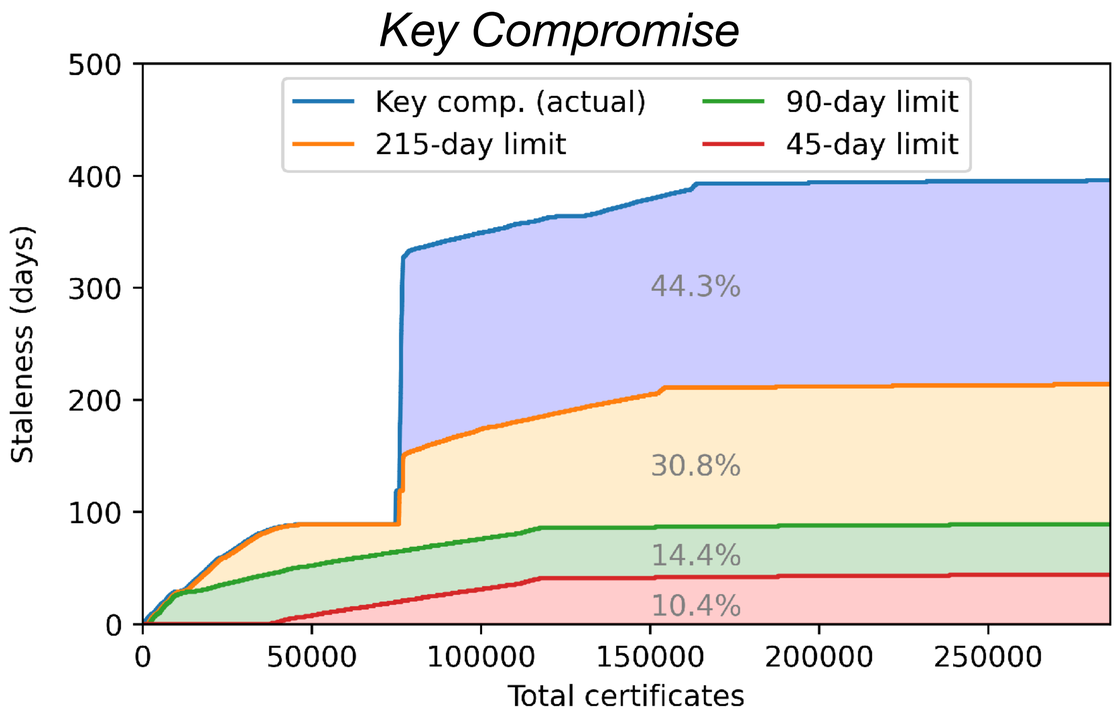

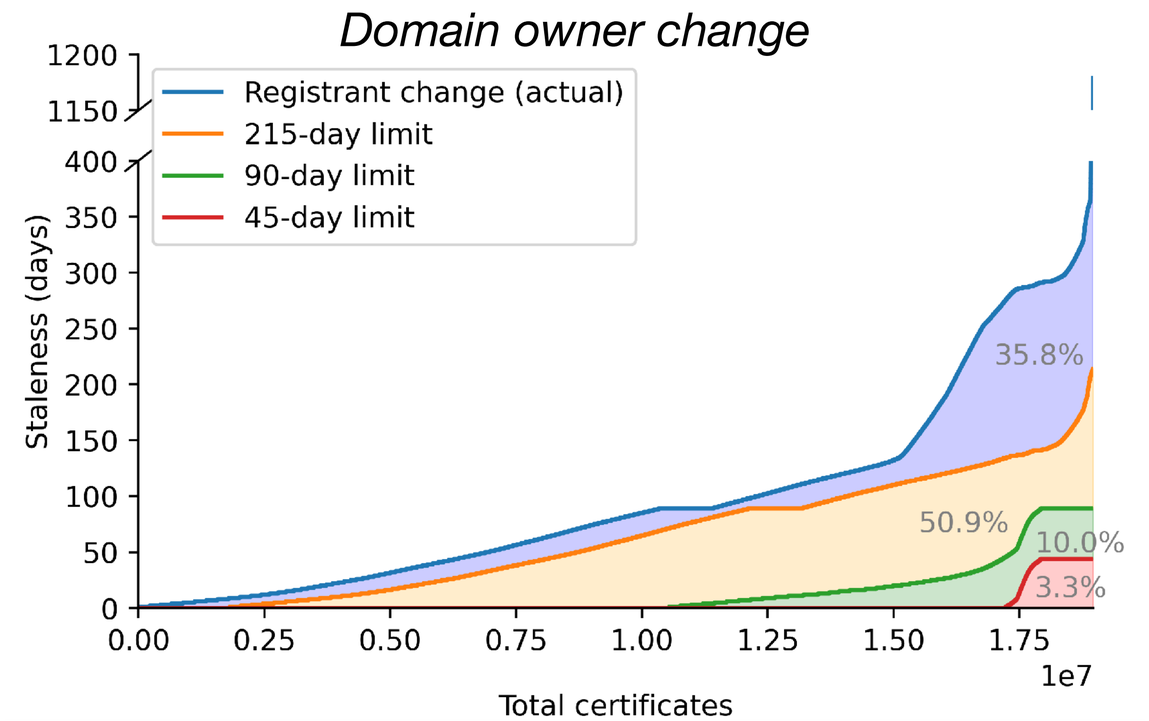

90-day limit =
75% decrease in time of third-party access to valid TLS keys

Conclusion

- TLS certificates are a caching mechanism to bind domain-to-key
- Stale TLS certificates —> third-party access to valid TLS keys for someone else's domain, enabling interception attacks
- This has affected at least 4 million domains since 2013

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- TLS certificates are a caching mechanism to bind domain-to-key
- Stale TLS certificates —> third-party access to valid TLS keys for someone else's domain, enabling interception attacks
- This has affected at least 4 million domains since 2013
- Revocation (cache invalidation) is ineffective; reducing certificate lifetimes (cache duration) is a promising direction
- Alternative solutions: placing keys closer to names and reducing the domain-to-key operational gap

Stale TLS Certificates

Investigating Precarious Third-Party Access to Valid TLS Keys

Zane Ma (he/him)
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2023.10.25

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